EXPERIMENTAL INVESTIGATION INTO EXPLOSIVE WELDING OF TUBE TO TUBE-PLATE

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MAY, 1982

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A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By

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to the
DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
MAY, 1982

CERTIFICATE

This is to certify that this work on "Experimental Investigation into Explosive Welding of Tube to Tube-plate" has been carried out by Shri Rajesh Kumar Baid under my supervision and it has not been submitted elsewhere for a degree.

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May, 1982

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ACKNOWLEDGEMENTS

I express my deep sense of gratitude and profound regards to Dr. G.S. Kainth for his keen interest and invaluable guidance in bringing up the present work.

I am thankful to Mr. R.C. Gupta, Mr. M.K. Vora, Mr. Y.J. Shah, Mr. I.K. Bhat, Mr. Arun Aggarwal, Mr. M.S. Panesar for their help, suggestions and discussions.

My thanks are also due to Mr. Hemant Gupta, Mr. Rakesh Kumar, Mr. Anil Srivastava, Mr. Raghuram, Mr. A.K.S. Chowdhary, Mr. S.P. Namballa, Mr. O.P. Bajaj, Mr. B.P. Bhartia, Mr. R.M. Jha, Mr. B.L. Sharma, Mr. Panna Lal and Mr. Sushil for their help at various stages.

I also wish to thank Mr. Ganguli for his assistance in preparing figures. I am thankful to Mr. J.P. Gupta for his excellent work in typing this work.

Finally, I am grateful to my G-TOP mates: Nirmal and Jayshankar GURU, Padhi, Anindyo, Firung, Dirac, Tripathi, Samal and Dheer Singh for ENCOURAGING me throughout my stay at I.I.T. Kanpur.

RAJESH KUMAR BAID

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Explosive welding is a solid state welding process wherein coalescence is affected by high velocity impact produced by a controlled detonation. The chief advantage of explosive welding process is that dissimilar metal combinations can be welded. Explosive welding has come to play an important role in many industries [1] such as - Aerospace (all explosively welded honeycomb), Transportation (explosively welded high speed reaction rail), Chemical process (clad veneers of expensive metal on low Carbon steel, fabrication of heat exchangers), Petroleum (bimetallic tubing and collar cladding pipelines), Shipbulding (high strength Aluminium to steel transition plates), Nuclear (clad fuel ducts, plugging of defective tubes), Cryogenic (fabrication of transition joints), Mining (explosively welded Copper grounding devices), Aircraft (wire reinforced Aluminium).

1.2 DEVELOPMENT OF EXPLOSIVE WELDING

Explosive welding was noticed during the first world war, when high-velocity pieces of sharpnel from the disintegration of metal casing of shells of bombs were observed to stick to steel stanchions or other metal surfaces. It was Carl [2] who performed experiments with two half-hard brass shims with the help of a booster charge of high detonation velocity and noted

welding under high-velocity impact for the first time. He also observed poorly formed interfacial waves between two shims.

In late 1950s several research workers started investigating the process of explosive welding for commercial applications. Simultaneously various theories about wave formation at the interface and selection procedure of welding parameters were proposed. Philipchuk [3] noted explosive welding in 1957 and recognised its value as a commercial tool by filling a patent application. Other early research workers in the field were Davenport and Duvall (1961), Cowan and Holtzman (1959, 1964), Tardif (1960), Holtzman and Rudershausen (1962), Boes (1962), Wills and Murdie (1962), Polaclyko and Williams (1964), Baron and Costello (1963), Reinheart and Pearson (1962), Bahrani and Crossland (1964) and Addison et al. (1963).

1.3 MECHANISM OF EXPLOSIVE WELDING

Explosive welding is achieved by placing an explosive charge in contact with one or both of the components. On detonation a pressure pulse is produced which imparts high velocity to the components. Oxide layers on the surfaces of the components are thus removed by the impact and, thereby, virgin surfaces are exposed for the bonding to take place.

The basic setup for explosive welding is shown in Fig. 1(a). The flyer plate and base plate are initially set apart by a distance known as stand-off gap δ. The explosive is separated from the upper surface of the flyer plate by a thin buffer plate of

rubber, cardboard or cork which protects the top surface of the flyer plate from any damage due to detonation of explosive charge. When the charge is detonated, a detonation wave propagates through the explosive charge at a velocity V_D. The impulse produced by the detonation front gives a velocity V_P to the flyer plate, which continues to move with this velocity until it impacts the parent plate. From Fig. 1(b) it is clear that effective angle of incidence β between the impacting bodies is somewhat greater than initial angle α [4]. It is noted from Fig. 2 that the flyer plate collapses in such a fashion that it appears to be hinged at point S at every instant. At the stagnation point S, the pressure is extremely high as compared to the shear strength of the material so that the two materials can be considered as inviscid fluids [5]. The flyer plate divides into two jets as shown in Fig. 2(a) (i) salient or main jet (ii) a re-entrant jet. The re-entrant jet contains not only the contaminated layer of the flyer plate, but also the surface layer of the parent plate. Thus the two virgin plate-surfaces come in contact under high pressure resulting in welding. Various researchers have shown experimentally that re-entrant jet is actually formed in explosive welding resulting in a loss of weight of the plates after collision [5].

Various velocity components can be written from Fig. 1(c) as [4]

$$\tan \beta = \frac{V_P \cos\alpha}{V_W - V_P \sin\alpha} \qquad (1)$$

$$V_F = \frac{V_P \cos\alpha}{\sin\beta} \tag{2}$$

$$V_W = \frac{V_D\ V_P}{V_P \cos\alpha + V_D \sin\alpha} \tag{3}$$

where

V_P = Velocity of the flyer plate

V_D = Detonation velocity of the explosive

V_F = Velocity of flyer plate relative to the point of impact

V_W = Velocity of collision point relative to the base plate

β = effective angle of incidence

α = initial angle of incidence

Velocity components for parallel arrangement can be written by putting $\alpha = 0$ in the above expressions, Fig. 2A.

The inclined set-up is necessary only when the effective angle of incidence, β, becomes less than 4° [4]. This occurs when high detonation velocity explosives are used.

1.4 WELD INTERFACES

The parameters effecting the explosive welding process are : Explosive charge and its detonation velocity V_D, stand-off gap δ, initial angle of incidence α, and properties of the flyer plate.

Depending upon controlling parameters for welding, nature of the welded interfaces [6] may be

(a) Straight or direct bond.

(b) Wavy interface.

(c) Uniform layer of solidified melt.

The following advantages of a wavy interface were pointed out by Davenport [7].

(i) the waves increase the total area of contacting surfaces by several times and expose a larger surface on the plates which subsequently bond under pressure.

(ii) very high strains in the thin surface layers greatly increase the mobility of the atoms and dislocations in these layers.

(iii) the waves provide a sort of mechanical interlocking between the two contacting surfaces.

Hay [8] concluded that the maximum shear strength of the weld corresponds to the wavy interface. In the case of straight bond there are often areas of no bonding, while in the extremely turbulent regime beyond the condition of wave formation, the shear strength decreases due to the formation of continuous melted metal zones [6]. But sometimes a direct interface may exhibit equally high strength as that obtained by a wavy interface [9]. Bahrani and Crossland [10] pointed out that 'waves act as interlocking serrations' in the shear tests but they further stated that 'the

welds with smaller interfacial waves give better results in tension tests and also in the bend test, whereas it was noted that larger waves produce stress concentration and sometimes are responsible for cracks'.

1.5 EXPLOSIVE WELDING OF TUBE TO TUBE-PLATE

The possibility of welding cylindrical surfaces was recognized as early as 1962, when Holtzman and Rudershausen[11] used implosive and explosive systems for producing duplex tubing. Other early researchers in the field of duplex tube welding were Doherty and Knop [12], Blazynski and Dara [13]. But the first useful application of explosive welding of cylindrical surfaces was that of tube to tube-plate welding which was first recognized by Crossland et al. [14].

The main use of the technique is in the manufacturing of heat-exchangers, where several tubes are to be fixed in a plate. At present, heat exchangers are mainly produced by roll bonding or conventional welding of the ends of the tubes to the plate. These methods usually end up with various deficiencies. Roll bonding often gives a function strength which is insufficient for the pressure, temperature and vibrations prevailing in many working situations. Conventional welding is limited by the fact that the weld length is actually no greater than the thickness of the tube wall. Tube to tube-plate welding of dissimilar metal combinations used in a number of applications involving corrosive or radiative fluids is difficult to achieve by the conventional

processes. Explosive welding offers a method of welding over most of the contact area.

Tube to tube-plate welding can be done by three different arrangements as shown in Fig. 3. In the inclined process (Fig.3(a)) patented under the name YIMpact, welding can be obtained with either high or low detonation velocity explosives. An alternative set-up (Fig. 3(b)) suggested by Bahrani et al. [15] uses a point charge of either high or low detonation velocity explosive, which gives rise to a spherical bulge in the tube which, when it impacts the wall of the hole in the tube-plate, causes an oblique impact on either side of the bulge. This produces two zones of welding with an area of no bonding directly under the bulge where normal impact occurs. The last arrangement (Fig. 3(c)) is the parallel tube to tube-plate set-up proposed by Crossland et al. [14], which is effective only with a low detonation velocity explosive. Various velocity components involved in the explosive welding of tube to tube-plate are shown in Fig. 4.

1.5.1 Selection of Parameters for Tube to Tube-Plate Welding

Crossland and Williams [16] proposed a series of welding parameters which formed the basis of the experimental programme related to cladding flat surfaces. For tube to tube-plate welding, they suggested that the following conditions should be satisfied [17].

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(1) The ratios V_W/V_{STP} and V_F/V_{ST} should be less than unity, so that the tube can achieve its required impact velocity just before the impact, where V_{STP} and V_{ST} are the sonic velocity in the tube-plate and tube respectively.

(2) The effective angle of incidence, β, should exceed some critical value below which it appears that the thickness of material stripped from the surfaces during impact is probably insufficient to remove the contaminant film, i.e., angle β dictates the thickness of the surface material which is forced into the jet. Shribman et al. showed that the amplitude of interfacial waves formed in explosive welding should be greater than the surface roughness of the plate. Bahrani and Crossland showed that the amplitude of the waves increase with β upto 10-20°, hence it was concluded that the minimum value of β is also dictated by surface roughness.

(3) There appears to be a minimum value of impact velocity, V_t, for any given material combination being welded, which depends on the stronger of the two material. Little information in available to establish a relationship between the critical velocity and static mechanical properties.

(4) The stand-off gap δ should be at least equal to half the tube wall thickness. By taking stand-off gap as one-quarter of the tube wall thickness, it was found that the weld becomes unacceptable unless the explosive charge is increased. This shows that if the stand-off gap is too small the velocity imparted to the tube before it impacts the tube-plate is too small. Usually the stand-off gap is kept inbetween half the wall thickness and wall thickness.

(5) There is a maximum value of surface roughness which can be tolerated above which weld becomes unacceptable, as stated in (2) also.

(6) The weld surfaces should be free from any contaminants such as water, oil and grease.

Though these welding parameters are not precise but they give sufficient information to enable the determination of charge weight approximately.

1.5.2 Tube Bulging

Bulging of the tube behind the tube-plate is one of the major problems arising in the welding of tube to tube-plate. Since tube to tube-plate welding is a confined process, a very high proportion of the pressure built-up due to a single explosion in the bore of the tube will dissipate into the nearest lower pressure region in front of the tube-plate. This results in an increased pressure at the front of the tube-plate which diverts a higher proportion of energy along the length of the tube and thus causes bulging behind the tube-plate [18]. With parallel arrangement, where length of the weld is greater than that of inclined arrangement, bulging of the tube becomes more severe. Bulging weakens the tube material and restricts the use of the process to low pressure applications. Sometimes due to bulging micro cracks appear on the tube, which may cause leakage of the fluid flowing through the tube.

Various researchers have studied the phenomenon of tube bulging under hydrostatic internal pressure. Since explosive welding

is a contact operation explosive working process, the dynamic pressure is at least ten times higher than that normally encountered in static loading [19]. Duffey and Krapp [20] studied the dynamic plastic response of a submerged cylindrical containment vessel. However their work cannot be directly applied to tube to tube-plate explosive welding, where the behaviour of the shock front and response of various points on the tube behind the face of the tube-plate needs to be known to estimate tube bulging.

1.5.3 Distortion of Adjoining Holes

In the tube to tube-plate welding, another limitation is posed by the distortion of the holes adjoining a hole in which a tube is being explosively welded. The distortion for a given explosive charge is related to ligament thickness, i.e., distance between two adjoining holes in a tube-plate. If the distortion is sufficiently large to cause a reduction in the hole diameter of the adjoining hole, the resulting reduction in the stand-off gap could very seriously affect the quality of the weld when a tube is welded into the adjoining hole. In order to use tube-plate face area economically, it is essential to use minimum ligament thickness [21]. Ligament thickness is governed by the impact energy of the tube striking the tube-plate. An increase in the tube wall thickness requires an increase in the explosive charge to impart necessary tube velocity and interfacial pressure for welding, which in turn increases the impact energy of the tube necessitating thicker ligament [22].

In order to solve the above problem Williams and Crossland [21] have done considerable work. They welded seven hole array tube-plate simulation with variable ligament thickness as proposed by Shribman et al. [23] so that information about distortion of adjoining holes could be found for six ligament thicknesses in one test. They checked the validity of the simulation by carrying out a number of tests on tube to tube-plate welding by varying the ligament thickness. They concluded that ligament distortion depends upon the kinetic energy of the explosion. They did most of the work on triangular pitching of tubes (which houses a greater density of tubes per unit area of tube-plate) and plotted distortion of the adjoining hole versus ligament thickness at various energy levels, and proposed the following relationship:

$$\Delta R = \left(\frac{K}{\sigma}\right) \frac{\rho V_t^2 D^2 t^{1/2}}{L^{3/2}} \tag{4}$$

where

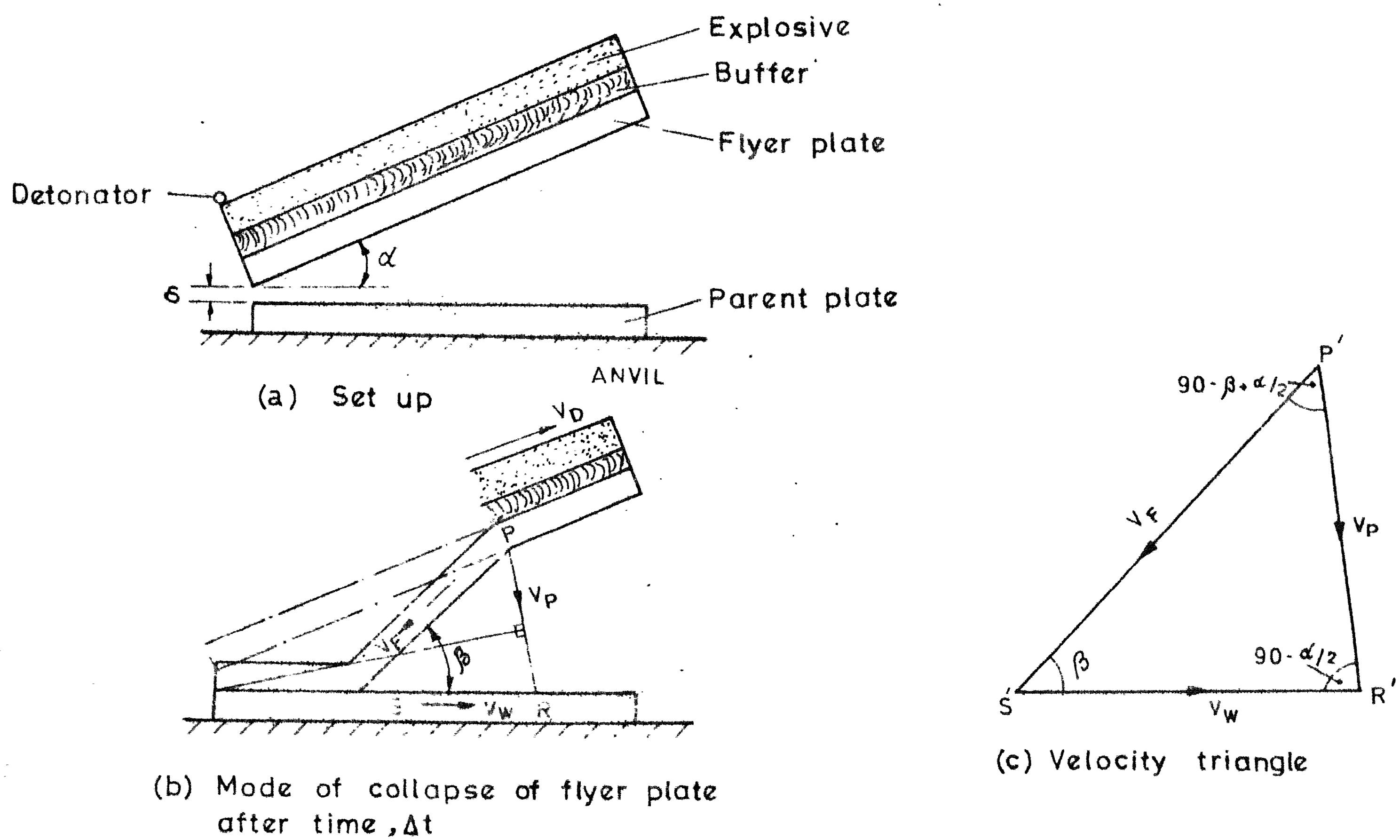
ΔR	=	radial distortion of the adjoining hole, mm
(K/σ)	=	constant for a particular tube-plate material
σ	=	representative stress for the tube-plate material, MN/m^2
ρ	=	density of the tube material, kg/m^3
V_t	=	impact velocity of the tube, m/sec
D	=	tube diameter, mm
t	=	tube wall thickness, mm
L	=	ligament thickness, mm

They proposed a design procedure to calculate centre line spacing with permissible distortion of the adjoining hole so that stand-off gap in the adjoining hole should at least be half the tube wall thickness.

1.6 OBJECTIVE OF THE PRESENT INVESTIGATION

In order to carry out welding of tube to tube-plate, it is essential that the tube bulging should not exceed acceptable limits. Since little information is available on the tube bulging due to a cylindrical charge, it is proposed to study the phenomenon experimentally. Experiments are also proposed to study ligament distortion.

The details of the experimental investigations are provided in the next chapter.



(a) Set up

(b) Mode of collapse of flyer plate after time, Δt

(c) Velocity triangle

FIG. 1 INCLINED ARRANGEMENT FOR EXPLOSIVE WELDING.

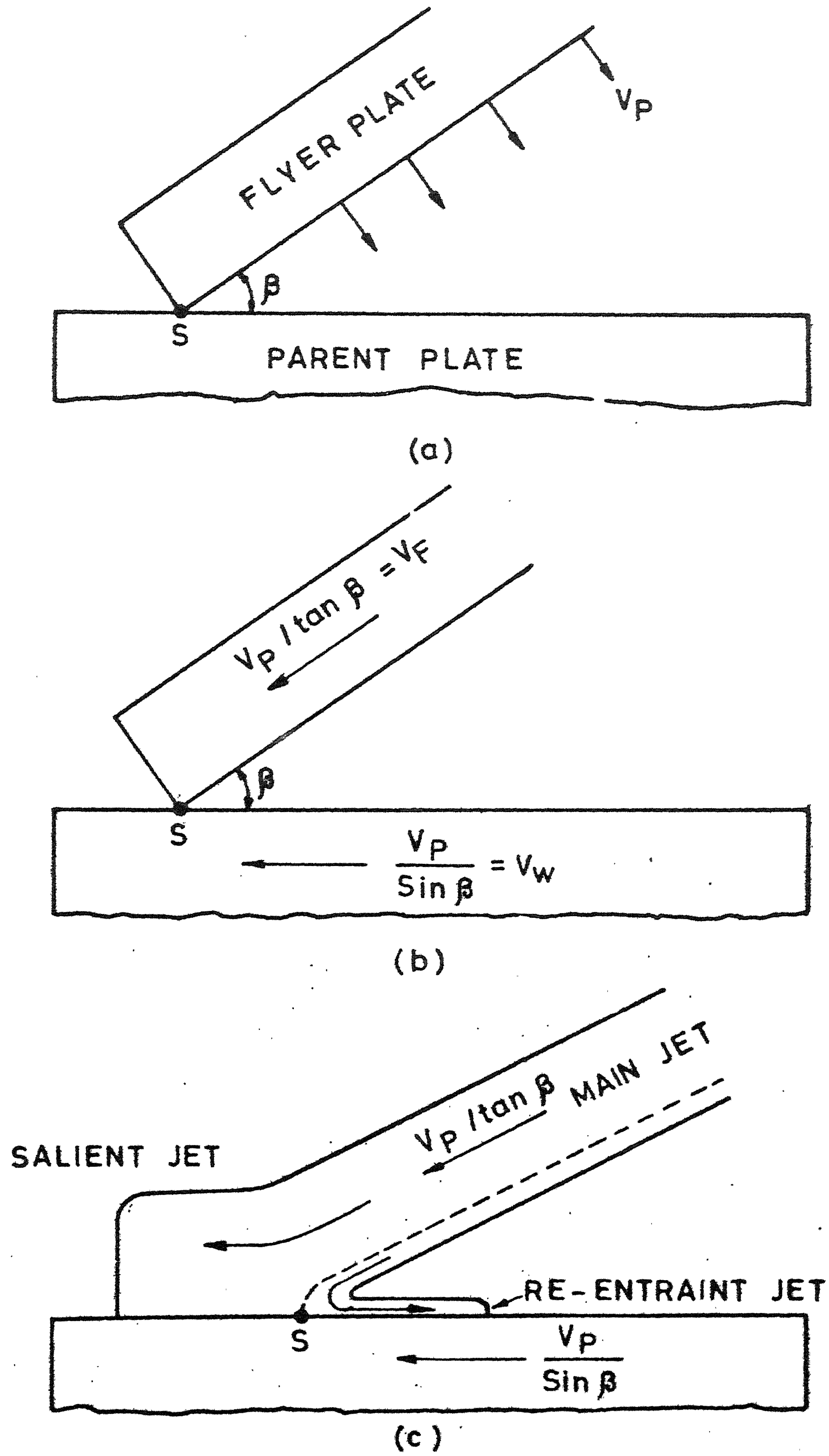


FIG.2 THE FORMATION OF THE METAL JET

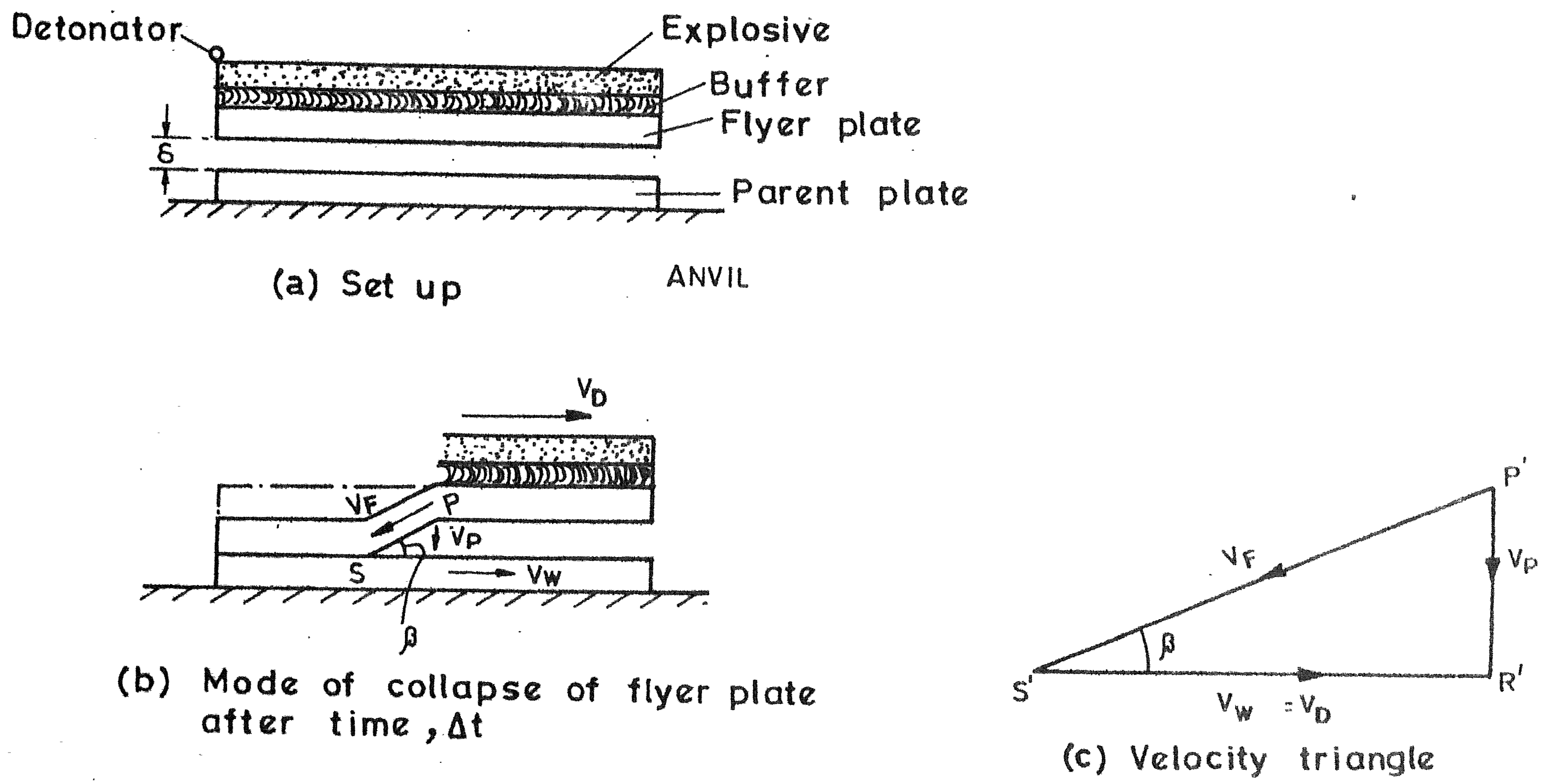


FIG. 2A PARALLEL ARRANGEMENT FOR EXPLOSIVE WELDING

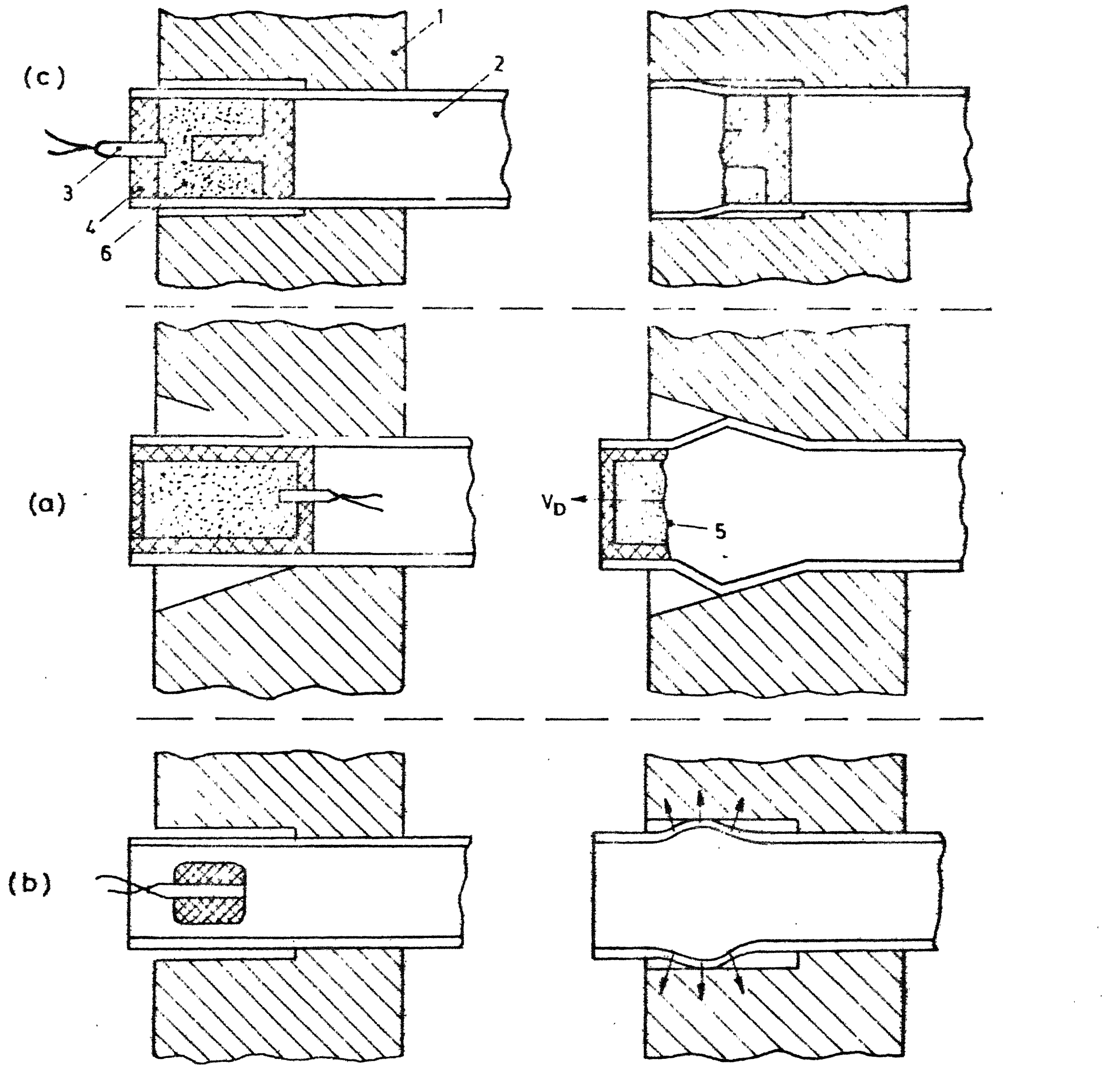


FIG. 3 COMMON CONFIGURATIONS FOR EXPLOSIVE TUBE TO TUBEPLATE WELDING. (a) Parallel arrangement (b) Inclined arrangement (c) Point charge system with spherical expansion

1 = Tubeplate 2 = Tube 3 = Explosive charge 4 = Detonator 5 = Detonation front 6 = Buffer

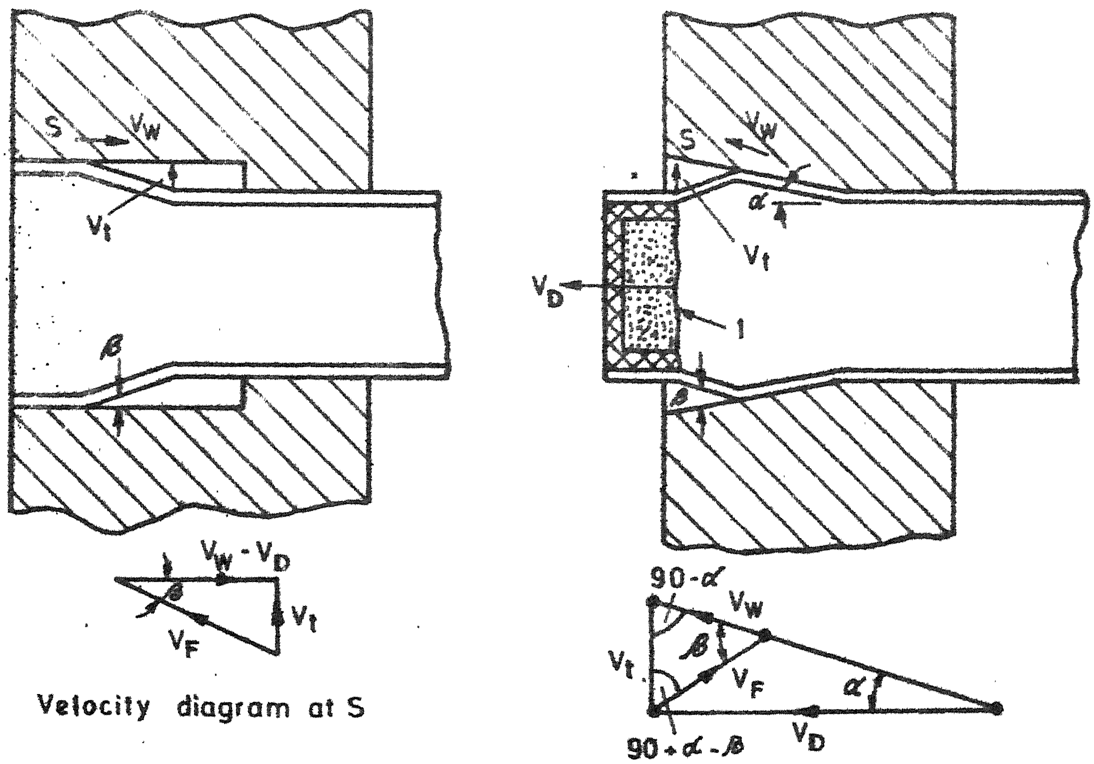


FIG. 4 GEOMETRY OF COLLAPSE FOR TUBE TO TUBEPLATE WELDING. V_F = Flyer plate (tube) velocity relative to point of impact. V_D = Detonation velocity. V_t = Radial velocity. V_W = Velocity of weld propagation. 1=Detonation front.

CHAPTER 2

EXPERIMENTAL INVESTIGATION

2.1 INTRODUCTION

Tube to tube-plate welding experiments are done by using parallel arrangement. Experiments are carried out by welding copper tubes to mild steel tube-plates by varying the position, quantity, and geometry of the charge. The bulging of the tube is measured. Experiments are also carried out on multi hole test specimens to study ligament distortion for variable ligament thickness.

Ultrasonic testing procedures is established to check the soundness of the welds.

Commerical SG 80% Nitroglycerin ($C_3H_5N_3O_9$) explosive is used in granular form with calorific value and the density as 1486 cal/gm and 1.4 gm/cm^3 respectively. The detonation velocity of the explosive is 2500 m/sec. Though the detonation velocity of the explosive varies with thickness and density of the explosive, however, in the present investigation the average value of detonation velocity is taken. REMO exploder and I.C.I. No.6 electric detonator are used. Miler sheet wrapped to cylindrical form is used as buffer between tube and tube-plate.

2.2 DETAILS OF EXPERIMENT

Following sets of experiments are done :

Preparation of tubes :

Tubes of required length are cut, and its outer surface is carefully marked to measure bulge after welding (Fig.5(b)). The tubes are cleaned with emery paper to remove any contaminant on the outer surface.

Calculation for charge weight :

To achieve successful welding, charge weight and configuration is chosen such that all the requirements of different conditions listed in Section 1.5.1 are satisfied.

The impact velocity V_t is kept higher than the minimum velocity needed to weld copper tube to mild steel tube-plate, i.e., higher than the range of 300-320 m/sec. [4].

Tube impact velocity is given by Gurney's equation [24]

$$V_t = \sqrt{2E_E} \times \sqrt{\frac{2R}{2 + R}} \times n \qquad (5)$$

where E_E = energy/unit mass of explosive which is converted into mechanical work.

$$R = \frac{m_S}{m_R + m_B} \qquad (6)$$

m_S = mass of explosive/unit length.

m_R = mass of tube/unit length.

m_B = mass of buffer/unit length.

n = factor accounting for the losses and its value ranges from 0.22 to 0.26 [25].

TABLE-1. VARIABLE CHARGE POSITION TESTS

CHARGE WEIGHT = 9.25 gms.

EXPT. NO.	L_A (mm)	L_X (mm)	L_B (mm)	RESULT
1.	25	55	75	Bulge with longitudinal crack.
2.	35	45	65	Very small bulge near the tube-plate face.
3.	45	35	55	No bulge.
4.	55	25	45	No bulge.
5.	65	15	35	No bulge.

The effective angle of incidence β is calculated using velocity diagram for parallel arrangement (Fig. 4(b)). It is ensured that β is always greater than 4° [4]. It is checked that the ratios V_W/V_{STP} and V_F/V_{ST} are less than unity. Sample calculations are given in Appendix-A.

Preparation of charge pack :

Miler sheet is cut to size and then wrapped on a perspex rod, to get the required dimensions shown in Fig. 6(b). One perspex cap is glued at one end, the required explosive charge is rammed into the miler sheet tube and, another cap with a hole in the center to accomodate the detonator is inserted.

Table 1 gives the details of the experiments done by changing the position of the charge (Fig. 6(a)) keeping the charge weight 9.25 gms.

The diameter of bulged tube is measured at the previously marked circles at intervals of 5 mm from the back end of the tube-plate. The bulging in terms of radial strain represented as $\ln(\frac{D+\Delta D}{D})$, where ΔD = amount of bulge, D = original diameter of the tube, is plotted against axial distance in Fig. 7.

Bulged tube (Expt. No. 1) is shown in Fig. 8. Tube with longitudinal crack is shown in Fig. 9.

SET - B : VARIABLE CHARGE WEIGHT TESTS

(1) Using solid charge :

The results of the experiments of SET-A show that there is no bulging of the tube when the distance of the back face of

TABLE-2 VARIABLE CHARGE WEIGHT TESTS (SOLID CHARGE).

EXPT. NO.	L_A (mm)	L_B (mm)	X (mm)	TOTAL WT. OF CHARGE (gms)	RESULT
6	25	75	70	32.25	Back end of the tube sheared off, and the tube-plate got a longitudinal crack.
7	45	55	50	23.10	Back end of the tube sheared off, and no crack in tube-plate.

the charge from the back end of the tube-plate, L_A, is greater than or equal to 45 mm. However bulging occurs for L_A less than 45 mm, and bulging is limited to a length of 35 mm for extreme cases when L_A is equal to 25 mm. Therefore experiments in SET-B(1) are designed to ensure bulging with back face of the charge at a maximum distance of 45 mm from the back end of the tube-plate (Fig. 10). Charge quantity is increased by increasing length of the charge keeping the front face of the charge at the same position for all cases, thereby, decreasing L_A. Since the mass per unit length of the charge is same as that of SET-A, information listed in 'calculation for charge weight' for successful welding applies to SET-B(1) also, Fig.10A.

Experimental details are given in Table 2 (Fig.10).

It is noted from the results (Table 2) that back end of the tube sheared off in both the experiments, even though the conditions listed in Section 1.5.1 are satisfied. This clearly shows that not only the mass per unit length of the charge but the total quantity of charge should also be considered for successful welding. To get successful weld, the quantity of the charge is reduced by using hollow charge.

Cracked tube-plate (Expt. No. 6) and back end of the tube-plate (showing signs of sheared off tube) are shown in Fig.11 and Fig. 12.

TABLE-3 VARIABLE CHARGE WEIGHT TESTS (HOLLOW CHARGE)

EXPT. NO.	L_A (mm)	L_B (mm)	X (mm)	TOTAL WT. OF CHARGE (gms)	RESULT
8	45	55	50	12.3	No bulge.
9	40	60	55	13.6	No bulge.
10	35	65	60	14.8	No bulge.
11	30	70	65	16.0	Bulge occurs with a thin longitudinal crack in the tube-plate.
12	25	75	70	17.3	Bulge occurs.

(2) Using hollow charge :

Fig. 13(a) shows the arrangement used with hollow charge (Fig. 13(b)). The back face of the charge is kept at a distance of L_A = 45 mm. from the back end of the tube-plate, and charge quantity is increased by increasing the length of the charge as done in SET-B(1). By making the charge hollow, the total impact energy is reduced, however it is ensured that the impact velocity V_t, is greater than the minimum required.

The details of the experiments are given in Table 3.

The diameter of the bulged tube is measured at the previously marked circles at intervals of 2.5 mm from the back end of the tube-plate. The bulging in terms of radial strain represented as $\ln(\frac{D+\Delta D}{D})$, is plotted against axial distance (Fig. 14).

Bulged tubes (Expt. No. 11 and 12) are shown in Fig. 15 and 16. Tube-plate with a thin longitudinal crack is shown in Fig. 17.

SET - C : MULTI HOLE VARIABLE LIGAMENT THICKNESS TESTS

Multi hole variable ligament thickness tube-plates as shown in Fig. 18 are prepared. Copper and stainless steel tubes are cut to size (Fig. 19(a)). Outer surfaces of the tubes are cleaned to remove any contaminants. Charge packs, with dimensions as shown in Fig. 19(b), are prepared in a similar manner as for SET-A. It is ensured that various conditions listed in Section 1.5.1 are

satisfied for successful welding. Copper and stainless steel tubes are welded in the central hole of two identical tube-plates. Radial distortion of the adjoining holes (ΔR) is measured and is plotted against ligament thickness, Fig. 20.

Multi-hole tube-plate with distortion of adjoining hole when a tube is welded in the central hole is shown in Fig. 21.

2.3 ULTRASONIC TESTING :

The pulse-echo method of ultrasonic non-destructive testing is used to check the soundness of the welded specimens. Ultrasonic flaw detector - UFD 6255 [26] is used to detect any appreciable discontinuity or inhomogeneity of elasticity or density in the specimen. Thus it is possible to find and, locate cracks or inclusions within the solid mass of specimen. The soundness of the joint bonded by various methods can also be tested [27]. Straight beam contact type probe having base diameter of 20 mm and 2.5 MHz pulse frequency is used.

2.3.1 Calibration of the Instrument

The instrument is calibrated by making a test block with a hole at a known distance of 6 cm as shown in Fig. 22(a). The back echo coming from the discontinuity (hole) is set at 10 cm on CRT Scale of the instrument, keeping the main bang at zero position as shown in Fig. 22(b). Thus a distance of 6 cm is represented by 10 cm on CRT scale.

2.3.2 Surface preparation of test piece

The surface of the test specimen must be capable of causing minimum attenuation of the sound waves transmitted from the transducer. Also the whole area of the probe base should be sealed over the test piece. Therefore, the upper surface of the welded specimen is machined by milling and surface grinding 24 mm flat at diametrically opposite position along the length of the tube-plate (Fig. 23(b)). A thin layer of oil is used as a couplant to provide a perfect acoustic coupling between the probe face and test piece surface.

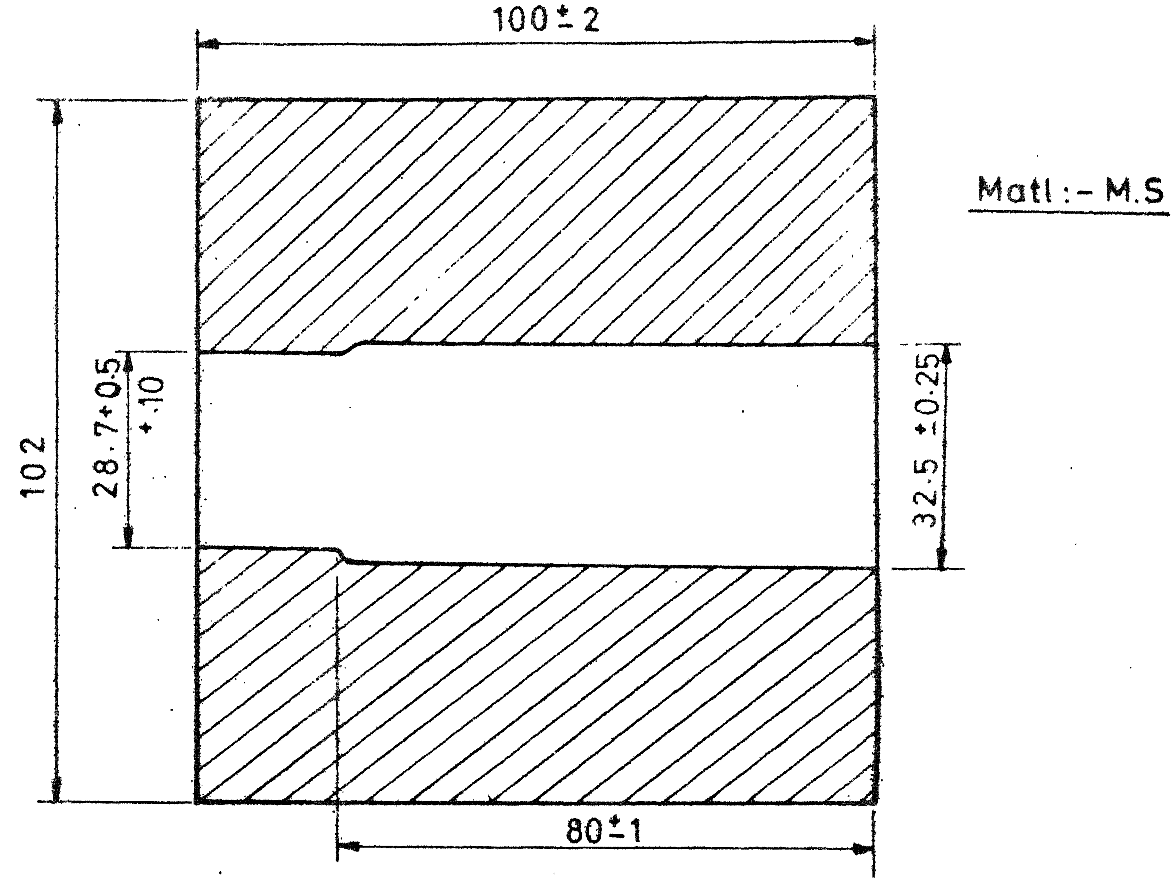
2.3.3 Interpretation of output signal

The signals coming from the specimen on the CRT scale are interpreted as shown in Fig. 23(a). When the centre line of the cylindrical probe is out of welding zone (as shown in position A), signal is reflected from the surface of the hole in the tube-plate as indicated by point a. Positions B and C represent probe position in the expected welding zone, depending upon the charge position. When the weld is perfect, the signal is reflected from the inner surface of the copper tube as indicated by point b. However, if the weld is not sound the signal is reflected from the surface of the hole in the tube-plate as indicated by point c. Sometimes two peaks (back echos) may appear on the CRT scale (one from the inner surface of the copper tube and another from the surface of the hole in the tube-plate), depending on the nature of flaw. At position D, the signal is reflected from the inner surface of the hole in the tube-plate as indicated by point d.

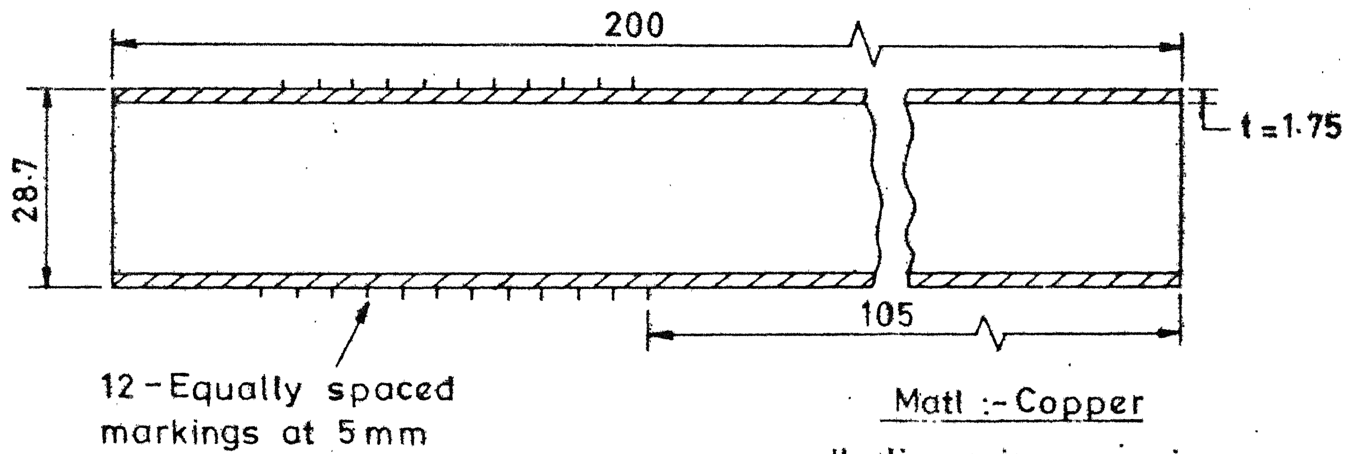
2.3.4 Results of the tests

Results of ultrasonic tests are shown in Figs. 24 and 25. Distance of the centre of probe (at an interval of 5 mm) from the back end of the tube-plate is plotted against readings of the calibrated CRT scale. Levels a', c' and b', d' in the Figs. 24 and 25 represent signals coming from point a, c, b and d (Fig. 23(a)) respectively. c" represents the average reading when two peaks appear on the CRT scale. Explosive charge position is also shown in Figs. 24 and 25. Calibration of the instrument is shown in Fig. 26. Fig. 27 shows signals from point a (Fig. 22(a)) on the CRT scale (out of welding zone). Figures 28 and 29 represent signals from perfectly welded surface and welded surface with a flaw for two different welded specimens.

Various results obtained in this chapter are discussed in the next chapter.

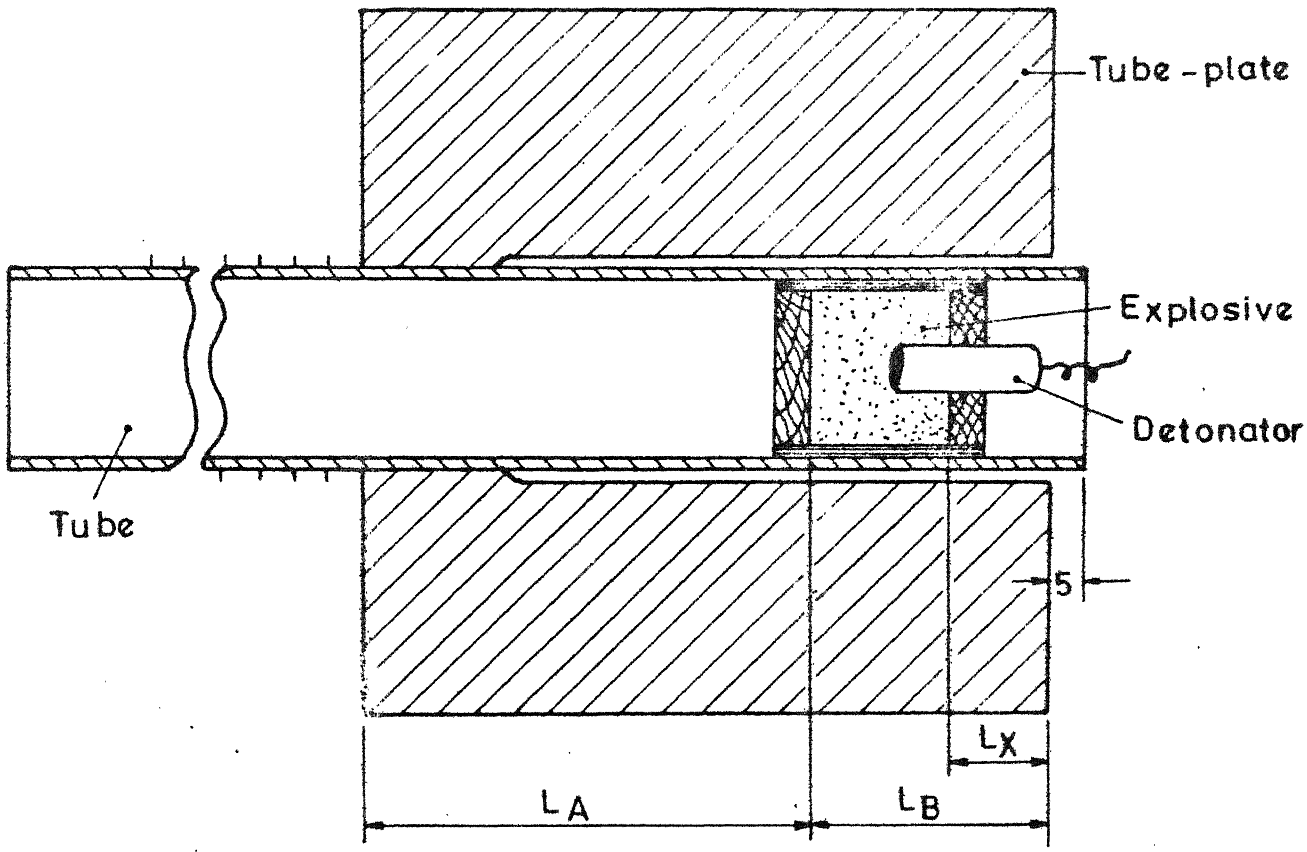


(a) Tube-plate

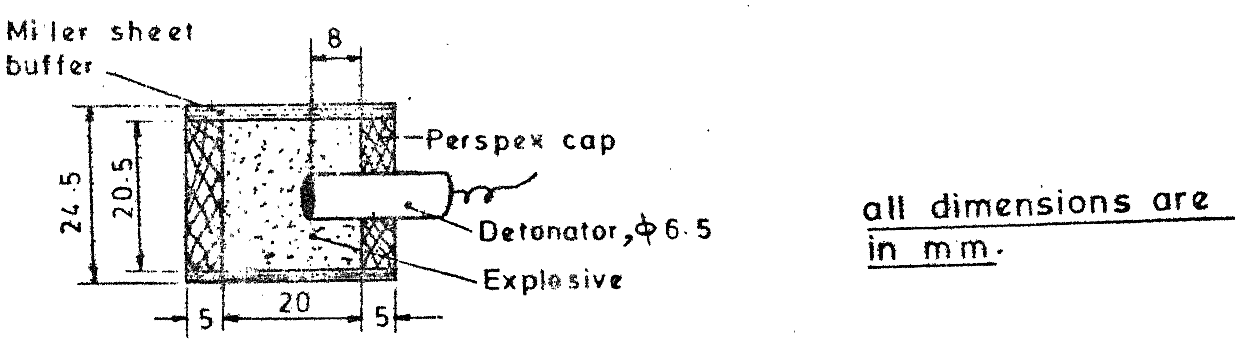


(b) Tube

FIG. 5 VARIABLE CHARGE POSITION TEST



(a) Exptl. configuration



(b) Charge pack

FIG.6 VARIABLE CHARGE POSITION TEST

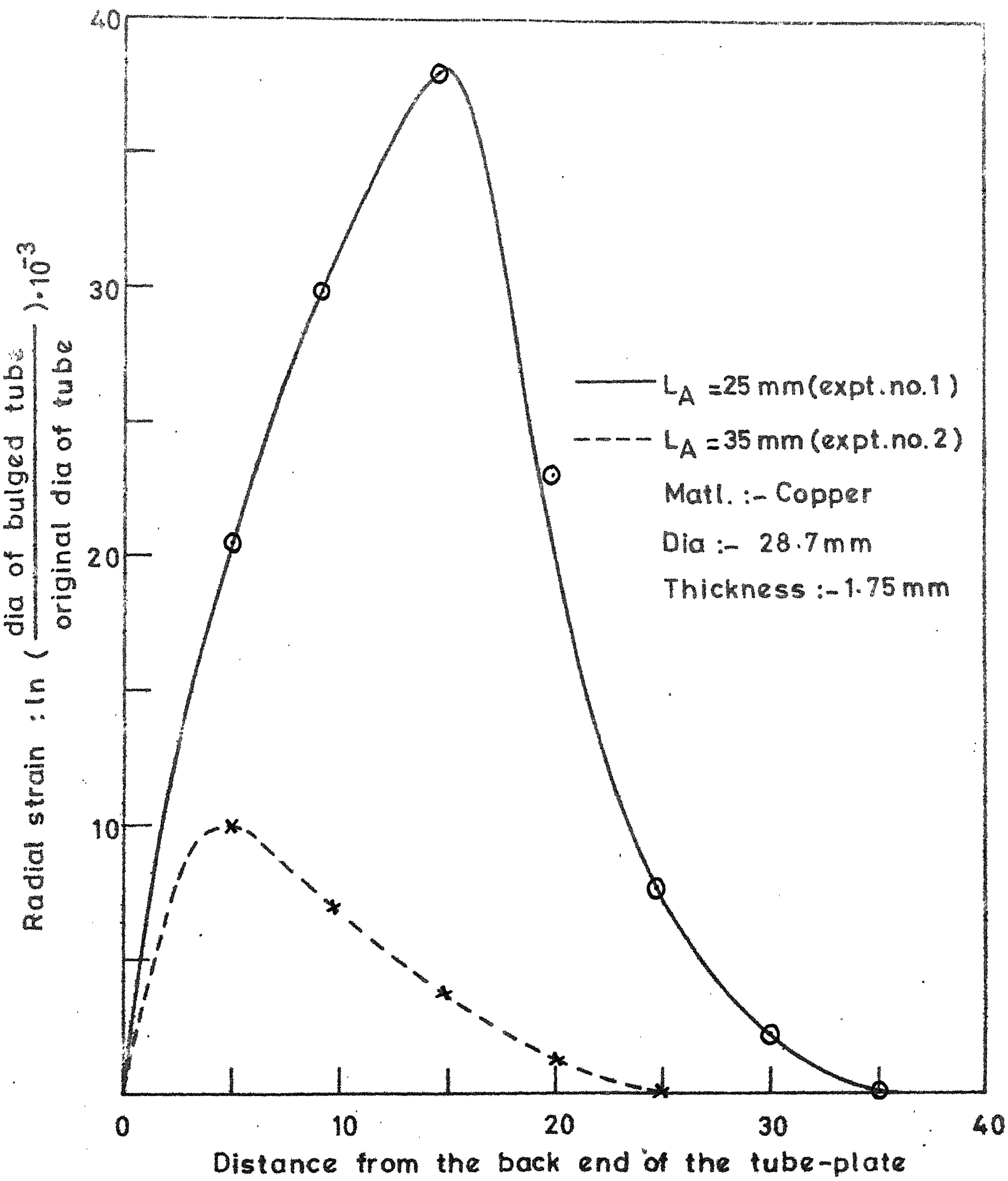


FIG. 7 RESULTS OF BULGING FOR VARIABLE CHARGE POSTION TEST

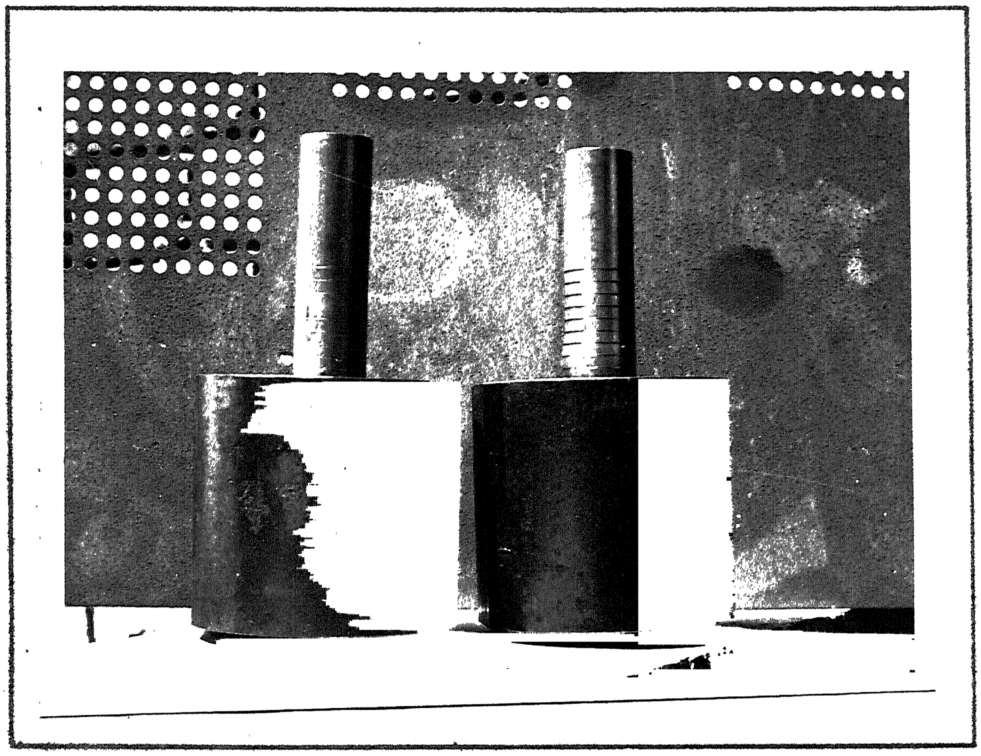


FIG. 8 BULGED TUBE (Expt. no.1)

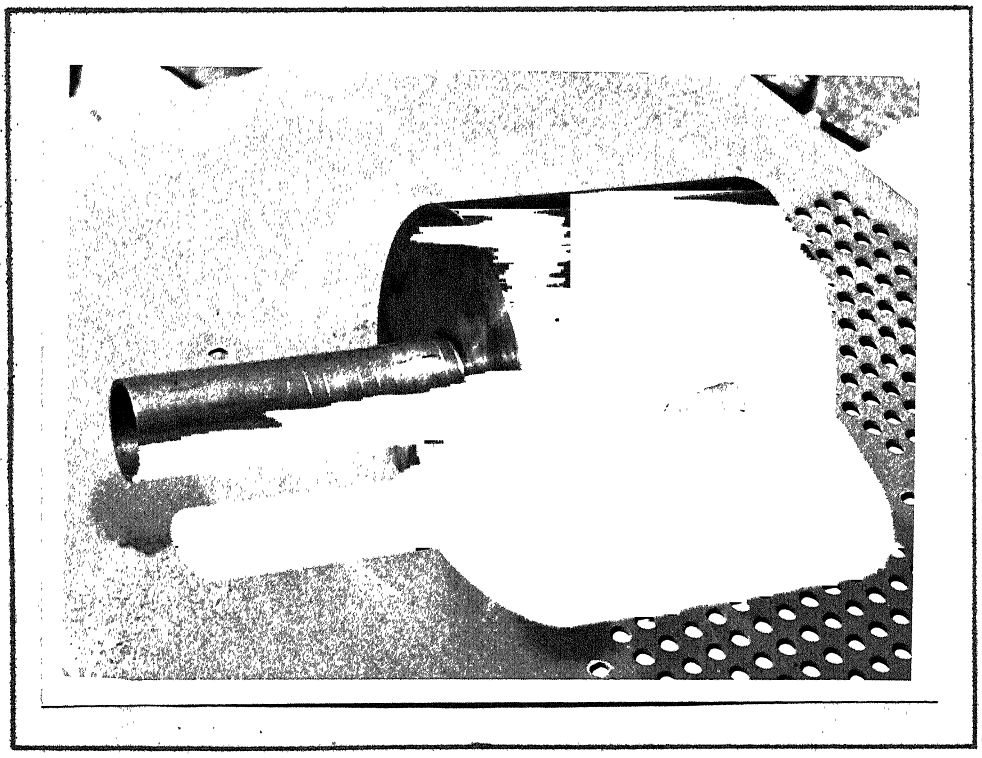
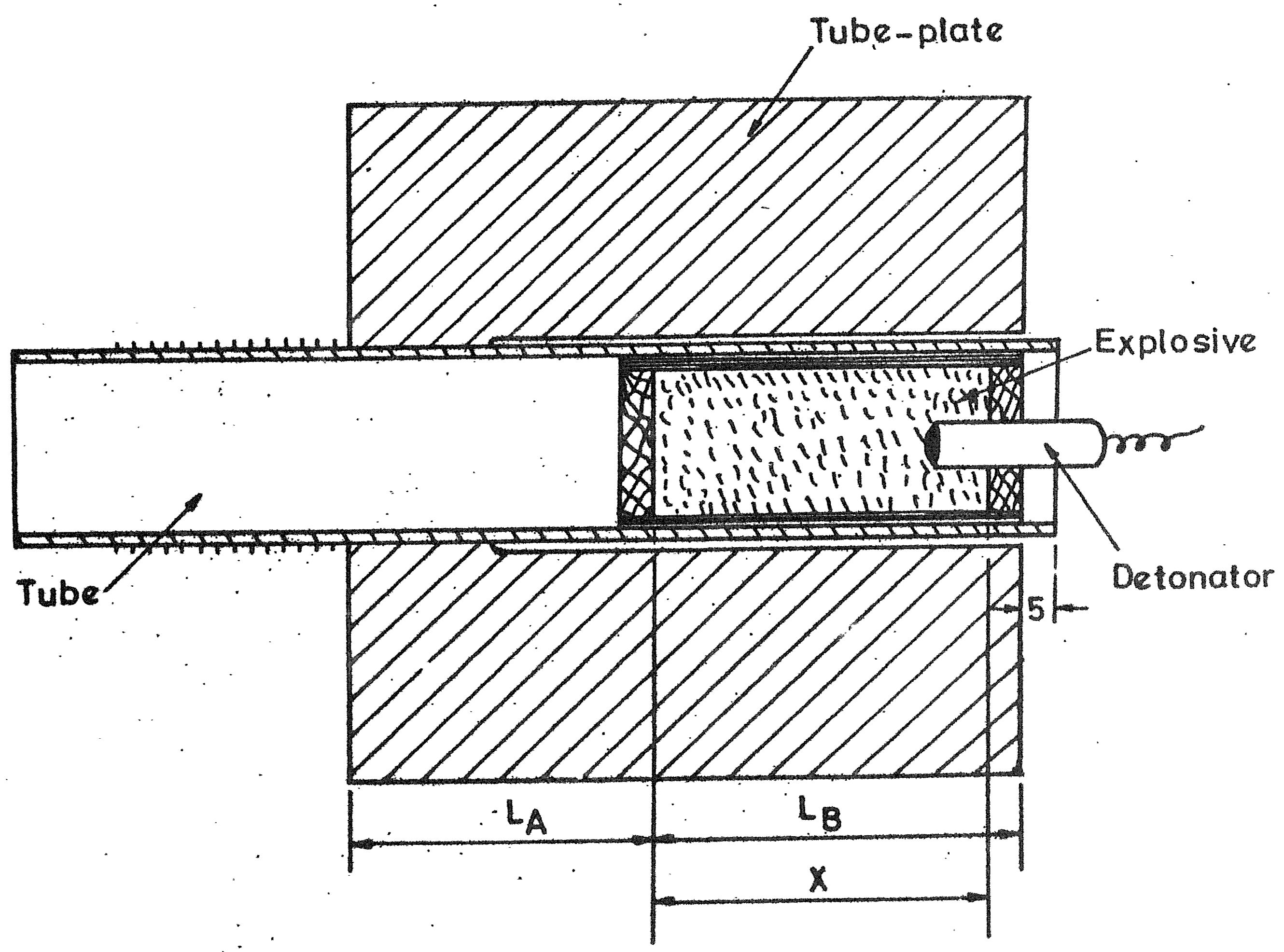
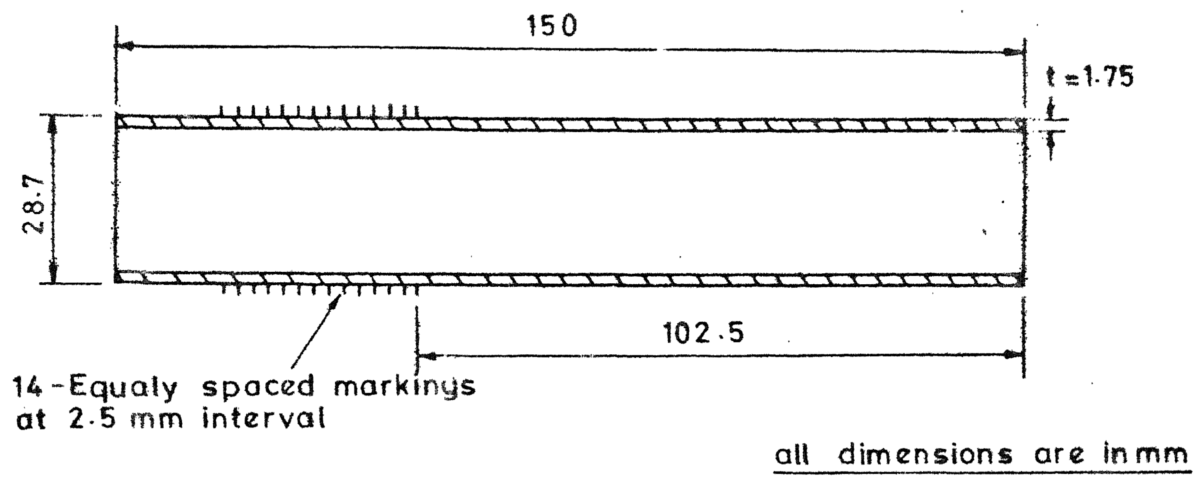


FIG. 9 TUBE WITH LONGITUDINAL CRACK (Expt.no.1)

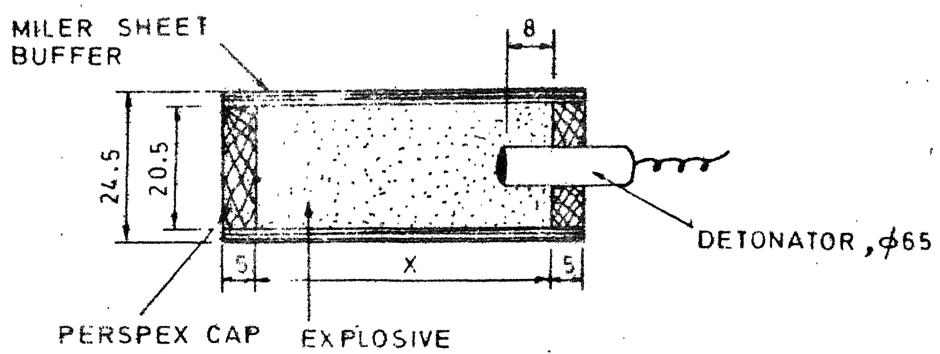


Exptl. configuration

FIG. 10 VARIABLE CHARGE WEIGHT TESTS (Solid charge)



(a) Tube



(b) Charge pack

FIG. 10A VARIABLE CHARGE WEIGHT TESTS (Solid charge)

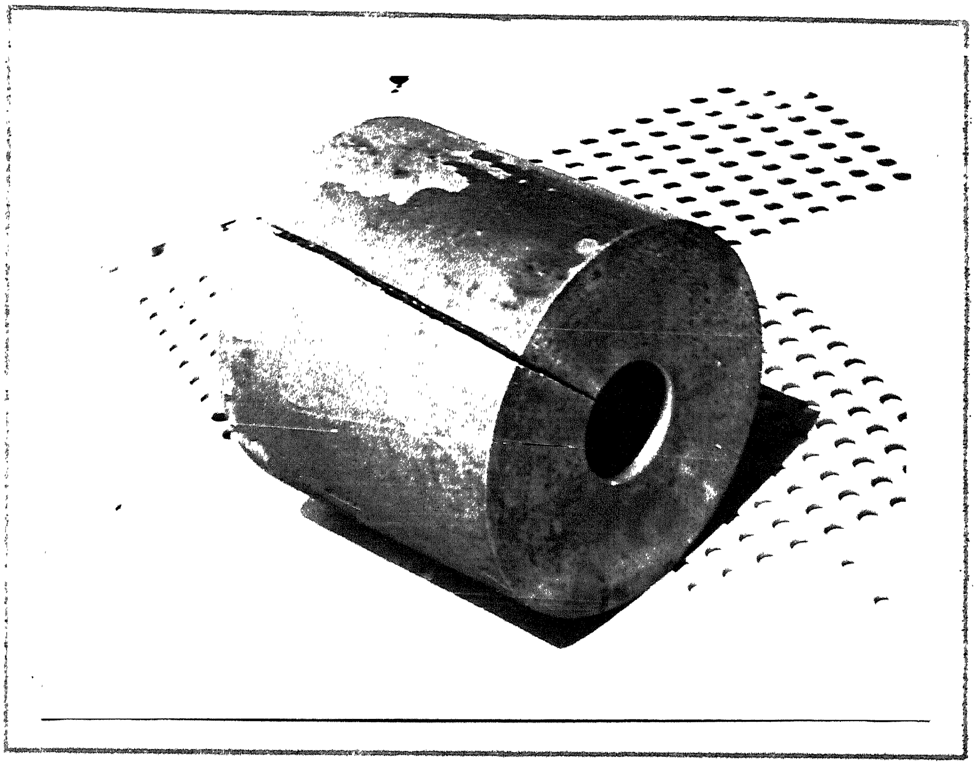


FIG. 11 TUBE-PLATE WITH A LONGITUDINAL CRACK (Expt. no. 6)

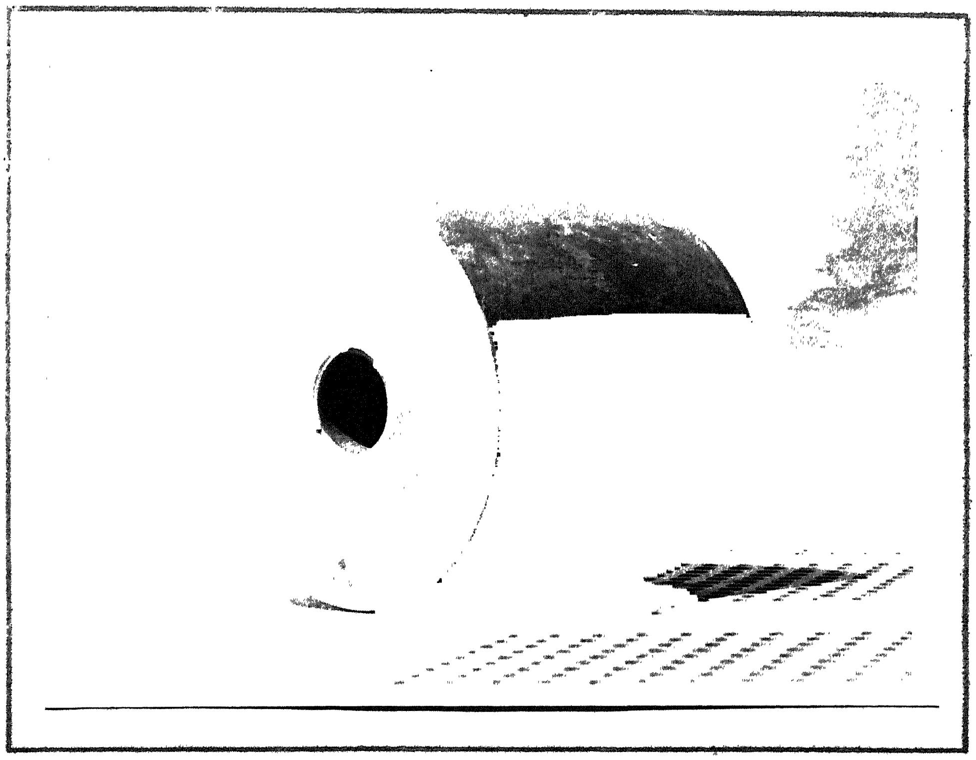


FIG. 12 TUBE-PLATE SHOWING SIGNS OF SHEARED OFF TUBE

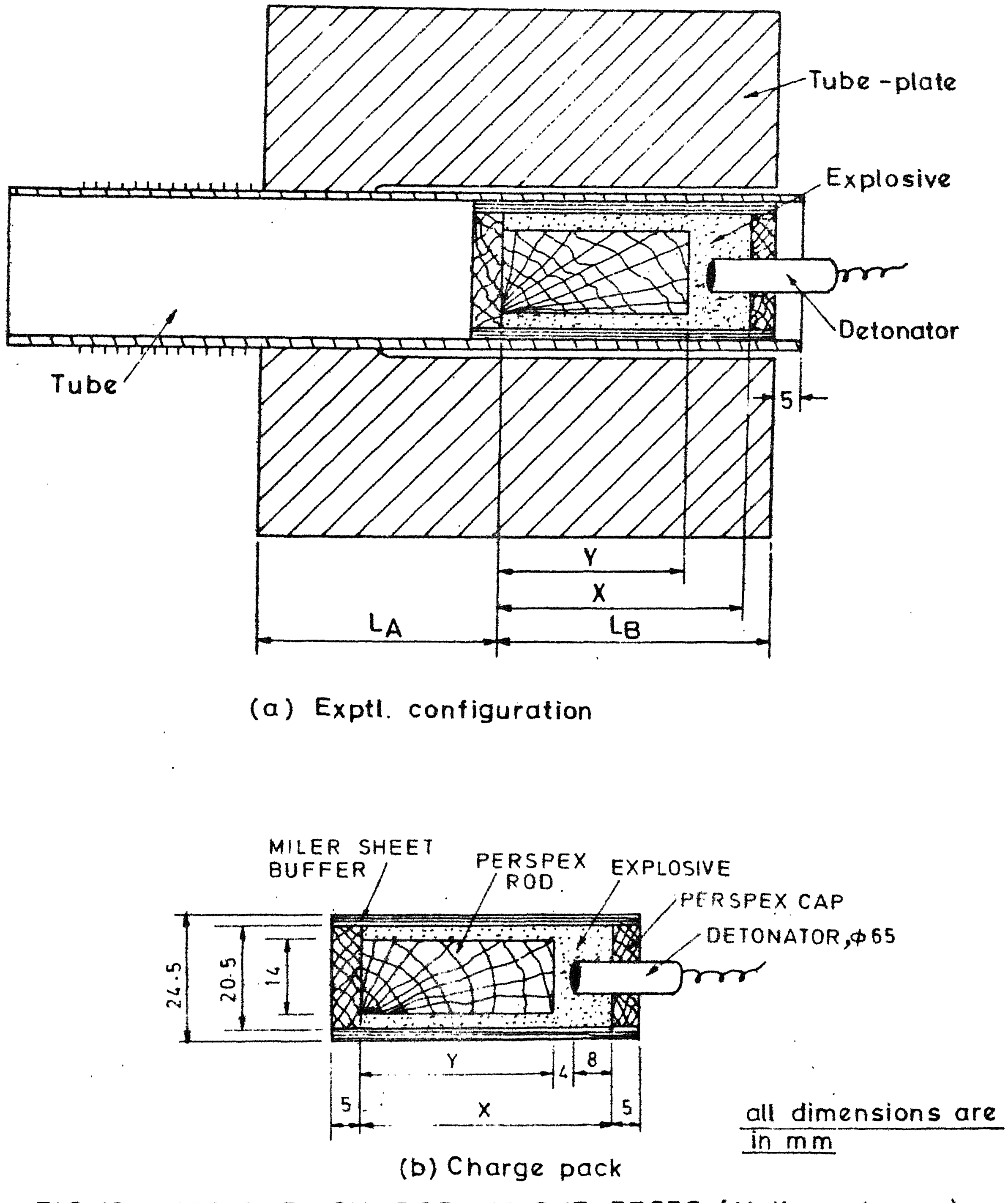


FIG. 13 VARIABLE CHARGE WEIGHT TESTS (Hollow charge)

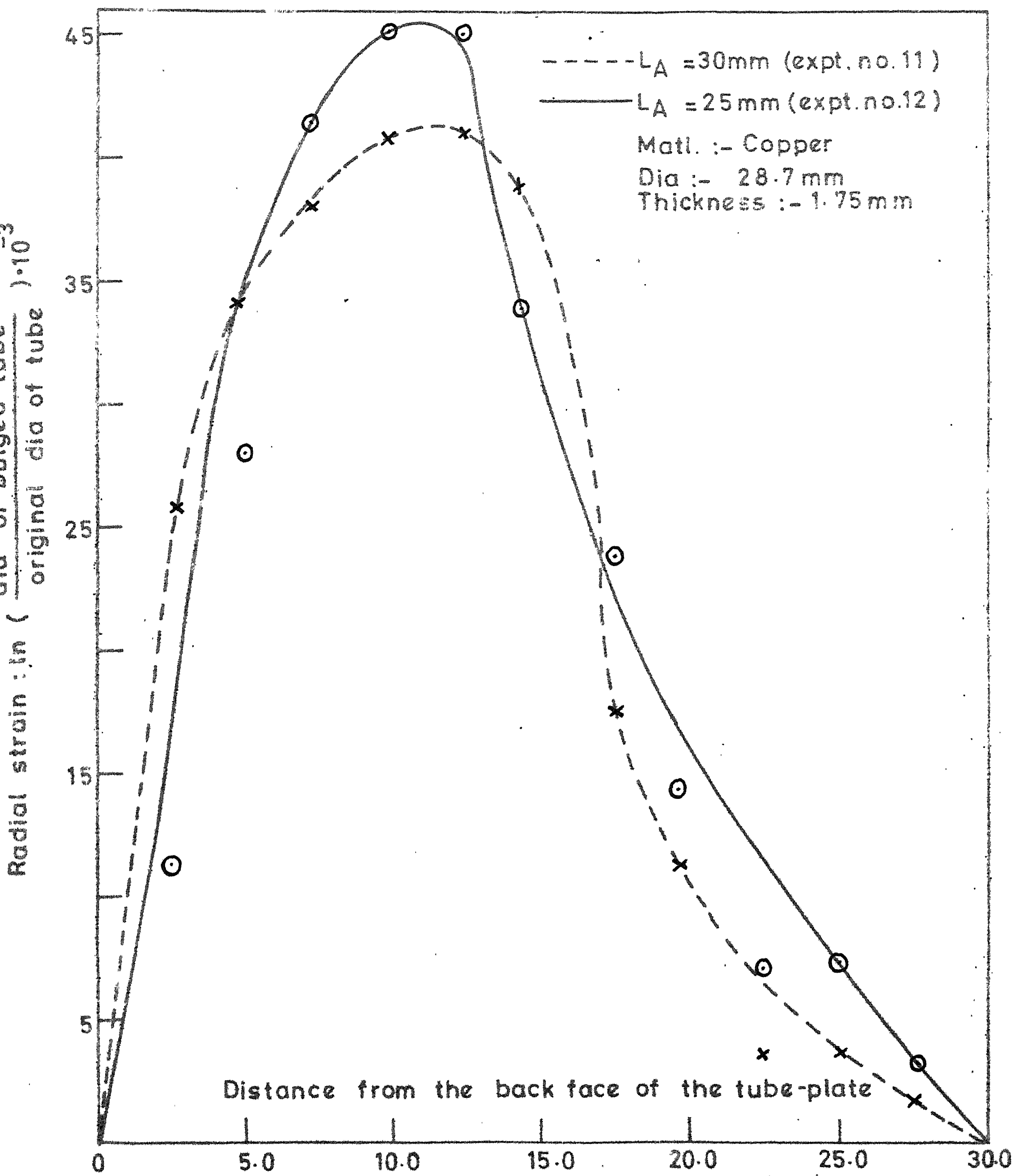


FIG.14 RESULTS OF BULGING FOR VARIABLE CHARGE WEIGHT TESTS (Hollow charge)

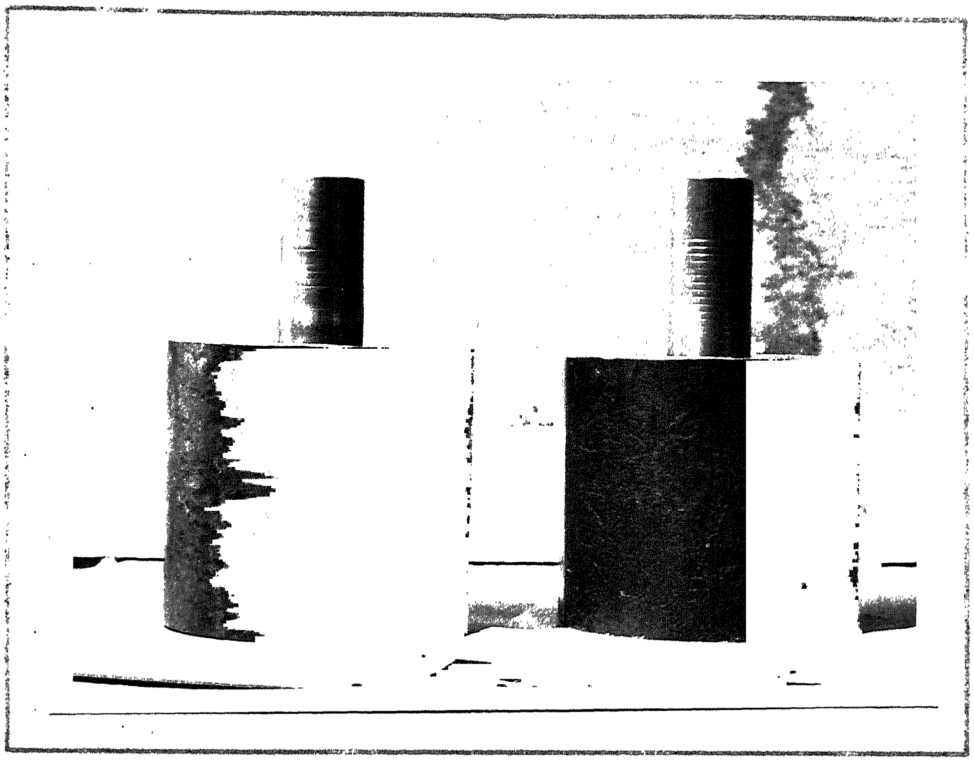


FIG. 15 BULGED TUBE (Expt.no.11)

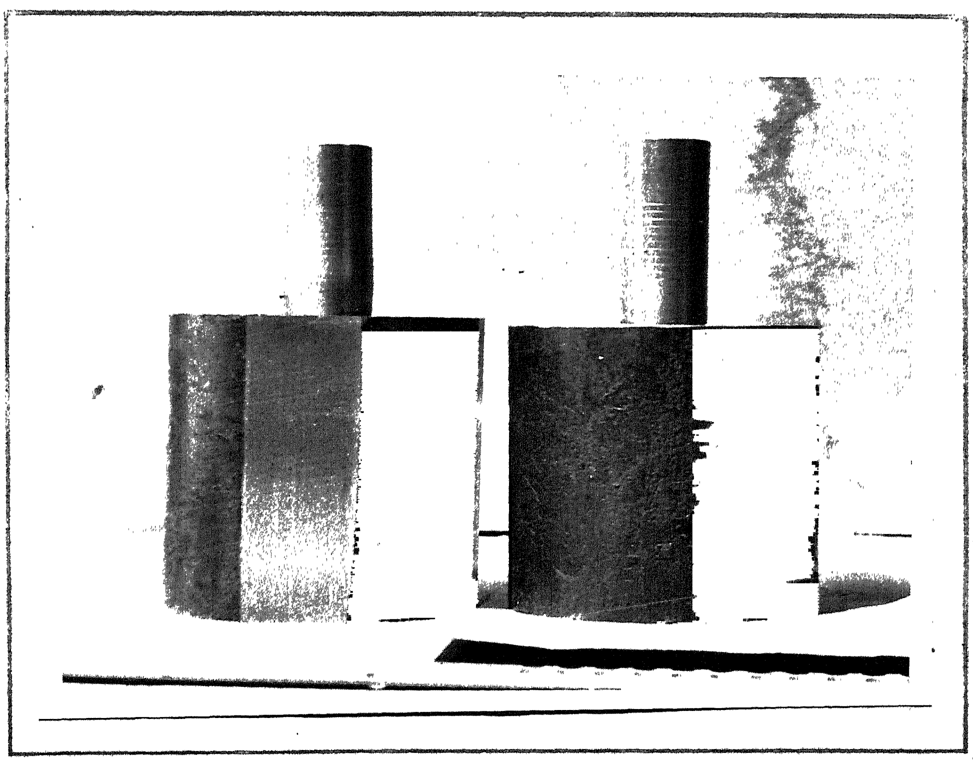


FIG. 16 BULGED TUBE (Expt.no.12)

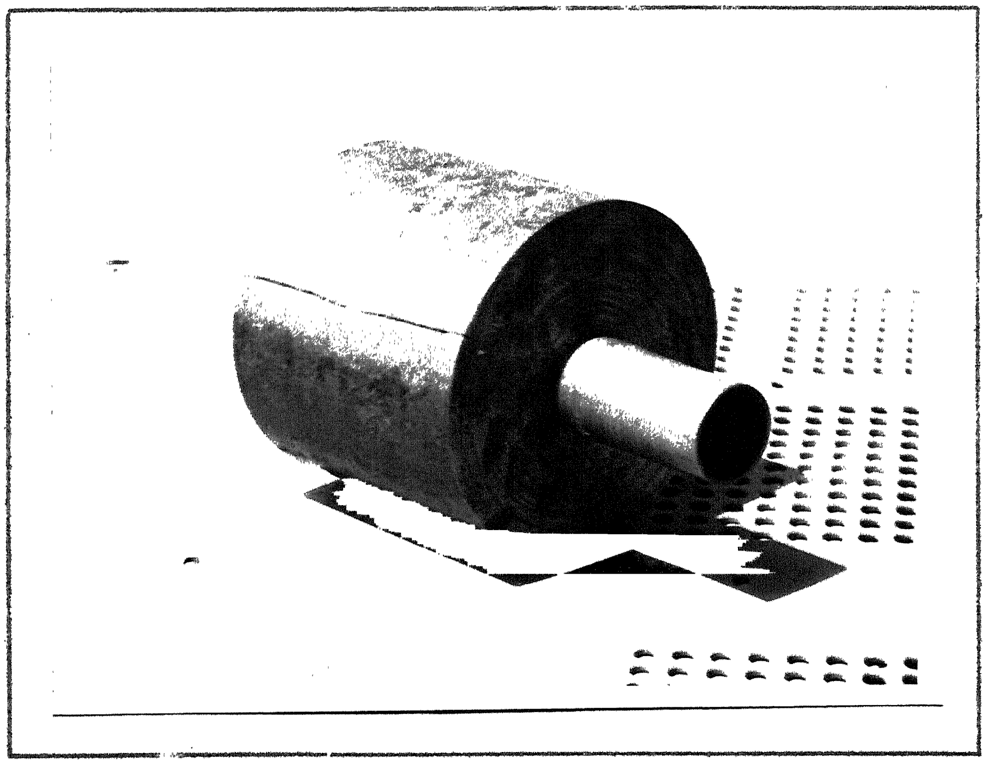


FIG. 17 TUBE PLATE SHOWING A THIN LONGITUDINAL CRACK (Expt. no. 11)

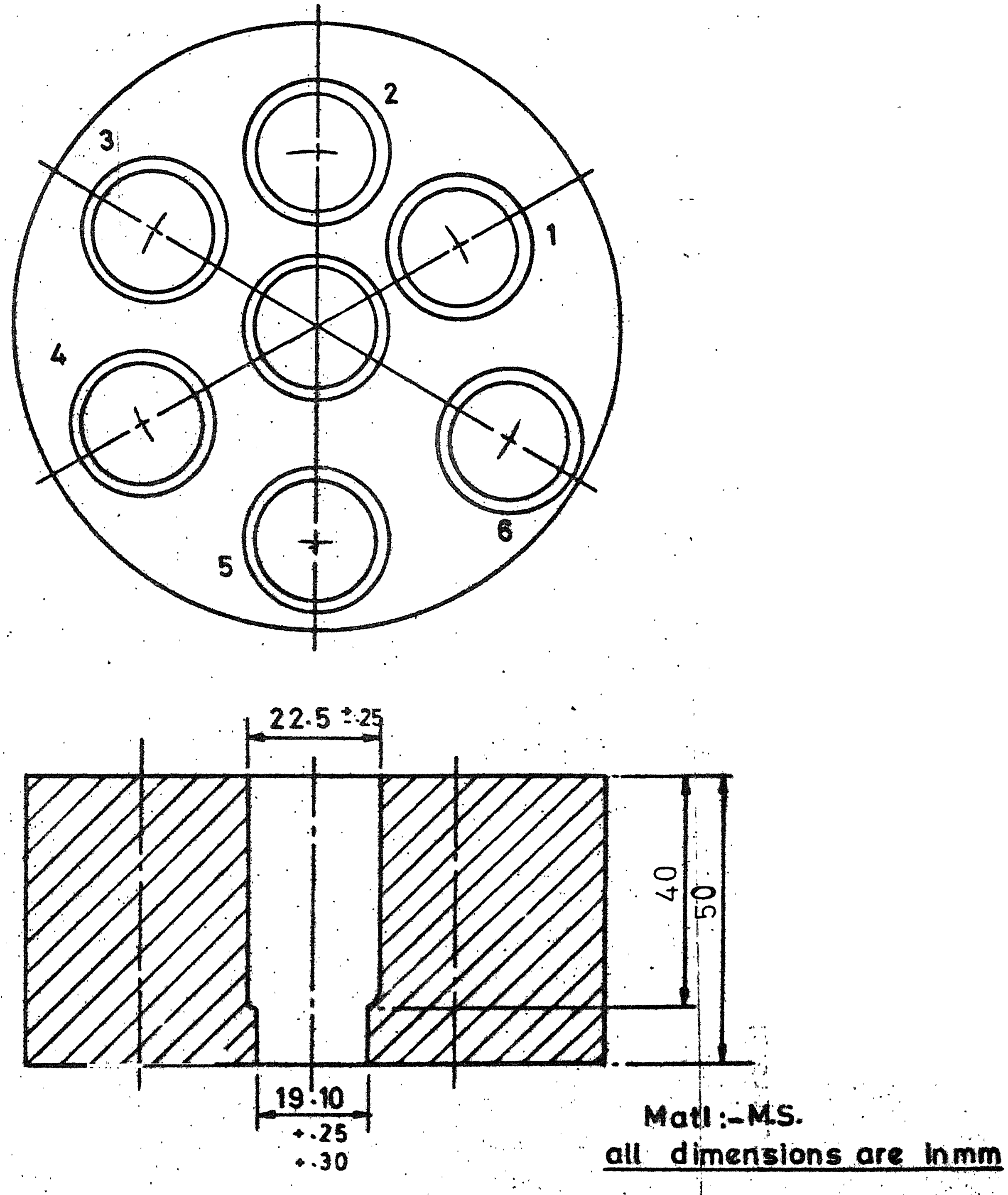
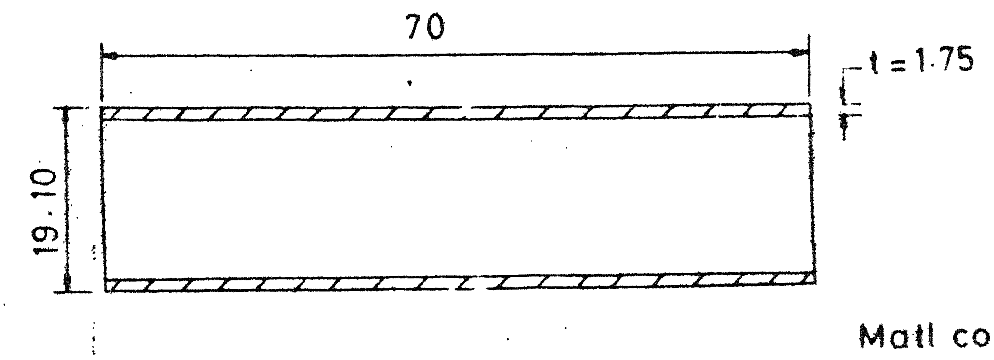
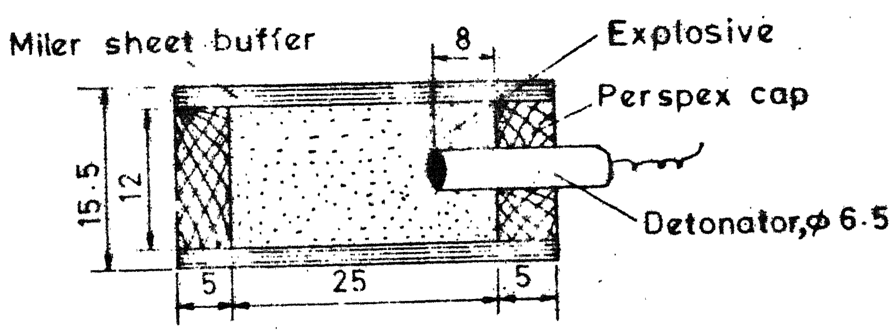


FIG. 18 MULTI HOLE TUBE-PLATE WITH VARIABLE LIGAMENT THICKNESS



(a) Tube



(b) Charge pack

all dimension are in mm

FIG. 19 MULTI HOLE VARIABLE LIGAMENT THICKNESS TESTS.

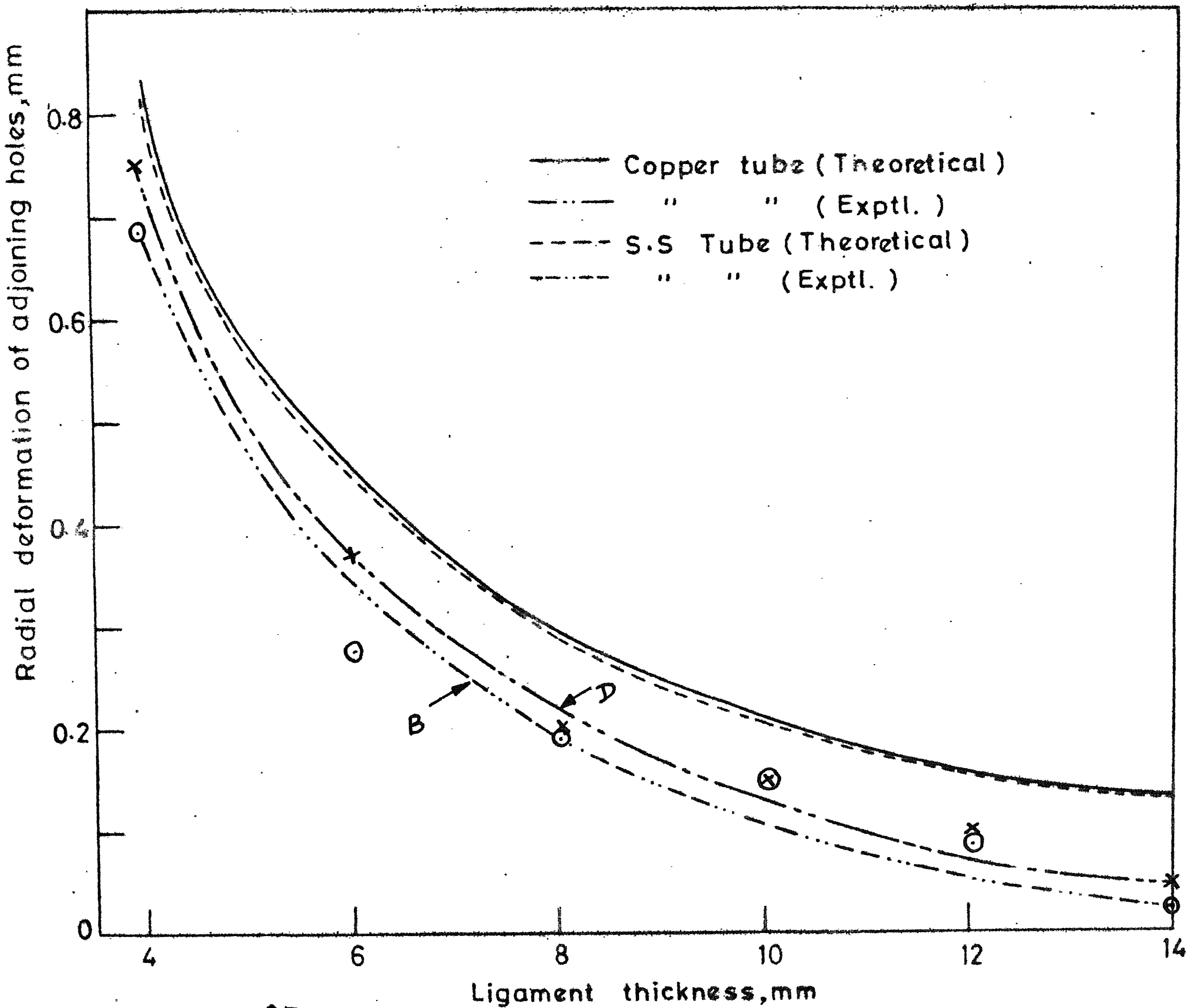
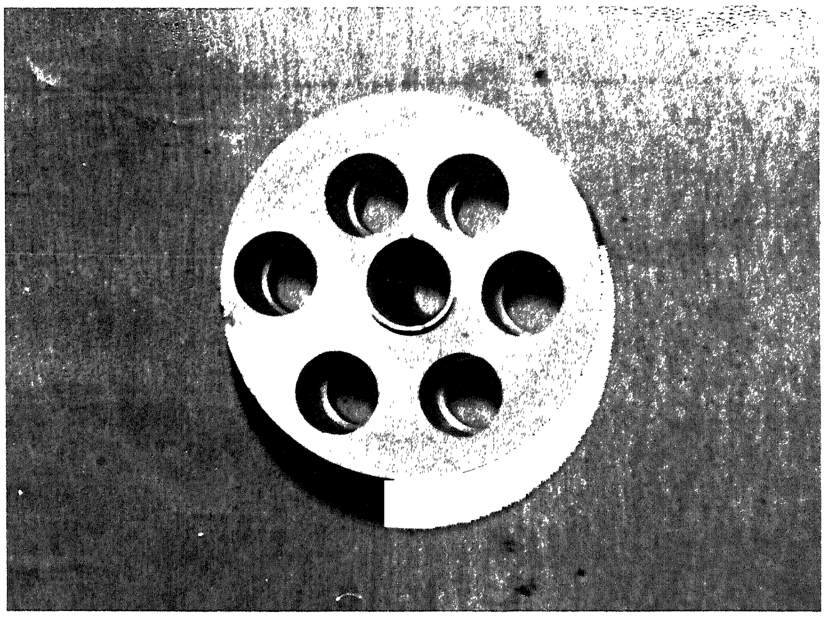
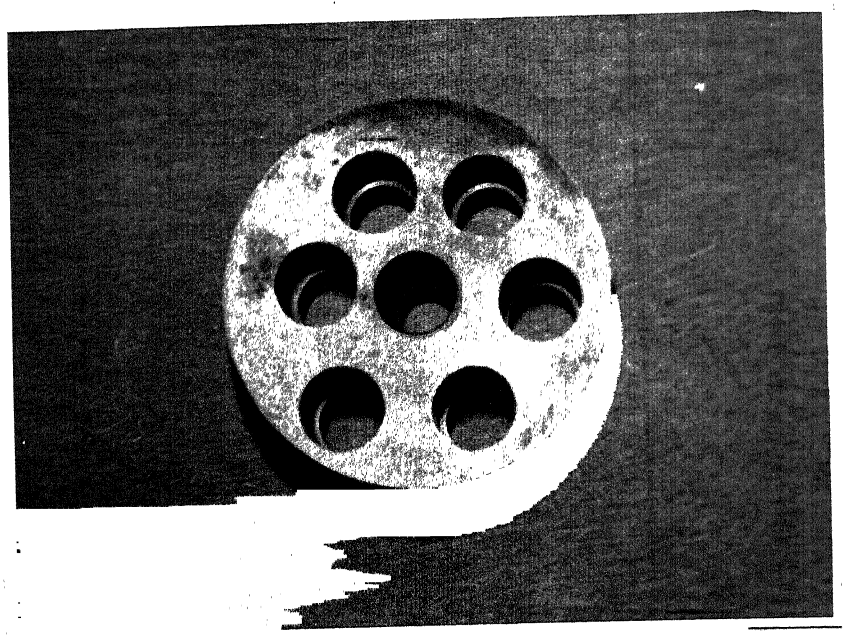


FIG. 20 VARIATION OF RADIAL DEFORMATION OF ADJOINING HOLE WITH LIGAMENT THICKNESS



(a) A stainless steel tube is welded in the central hole



(b) A copper tube is welded in the central hole

FIG. 21 MULTI HOLE TUBE PLATE WITH VARIABLE LIGAMENT THICKNESS

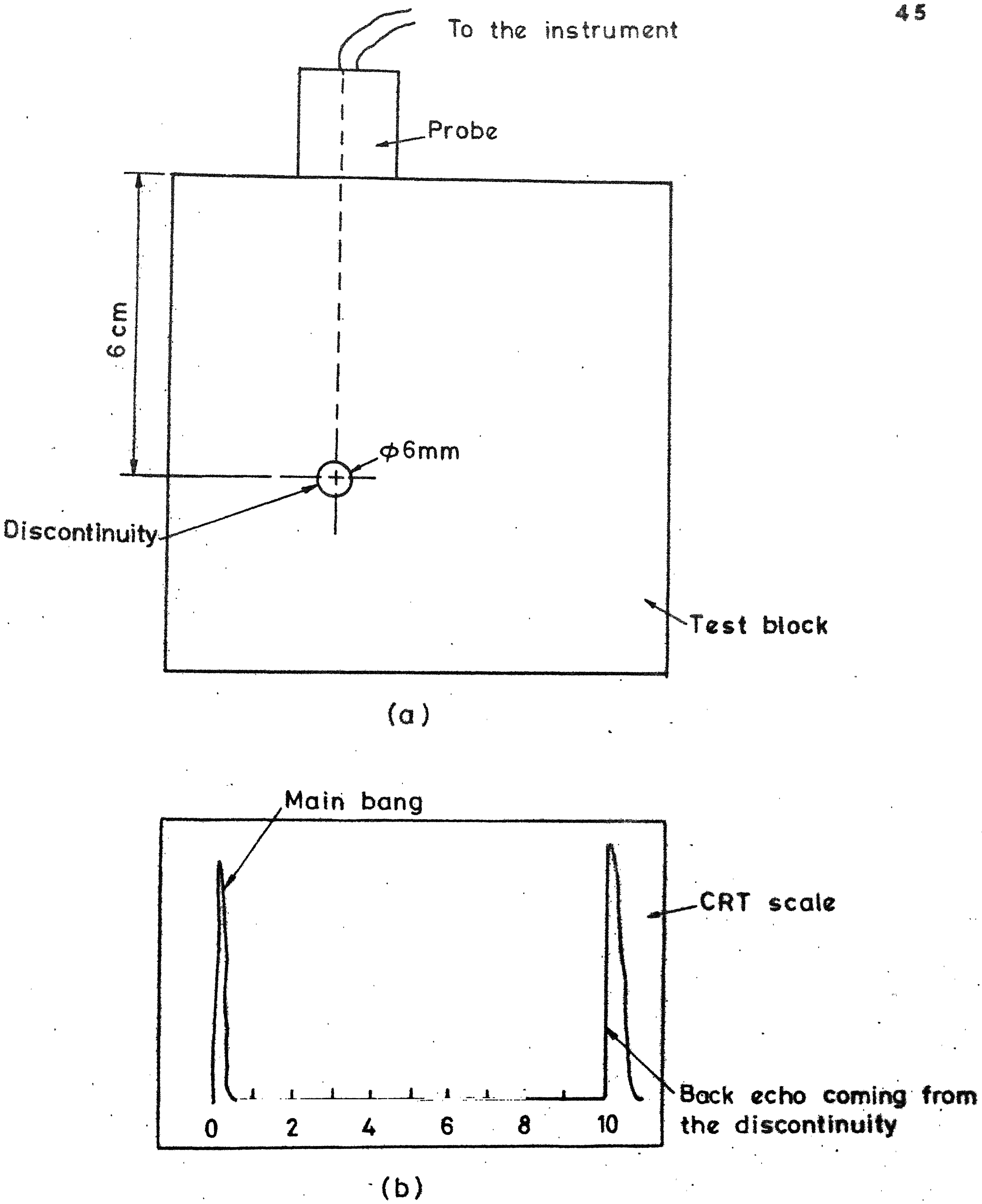
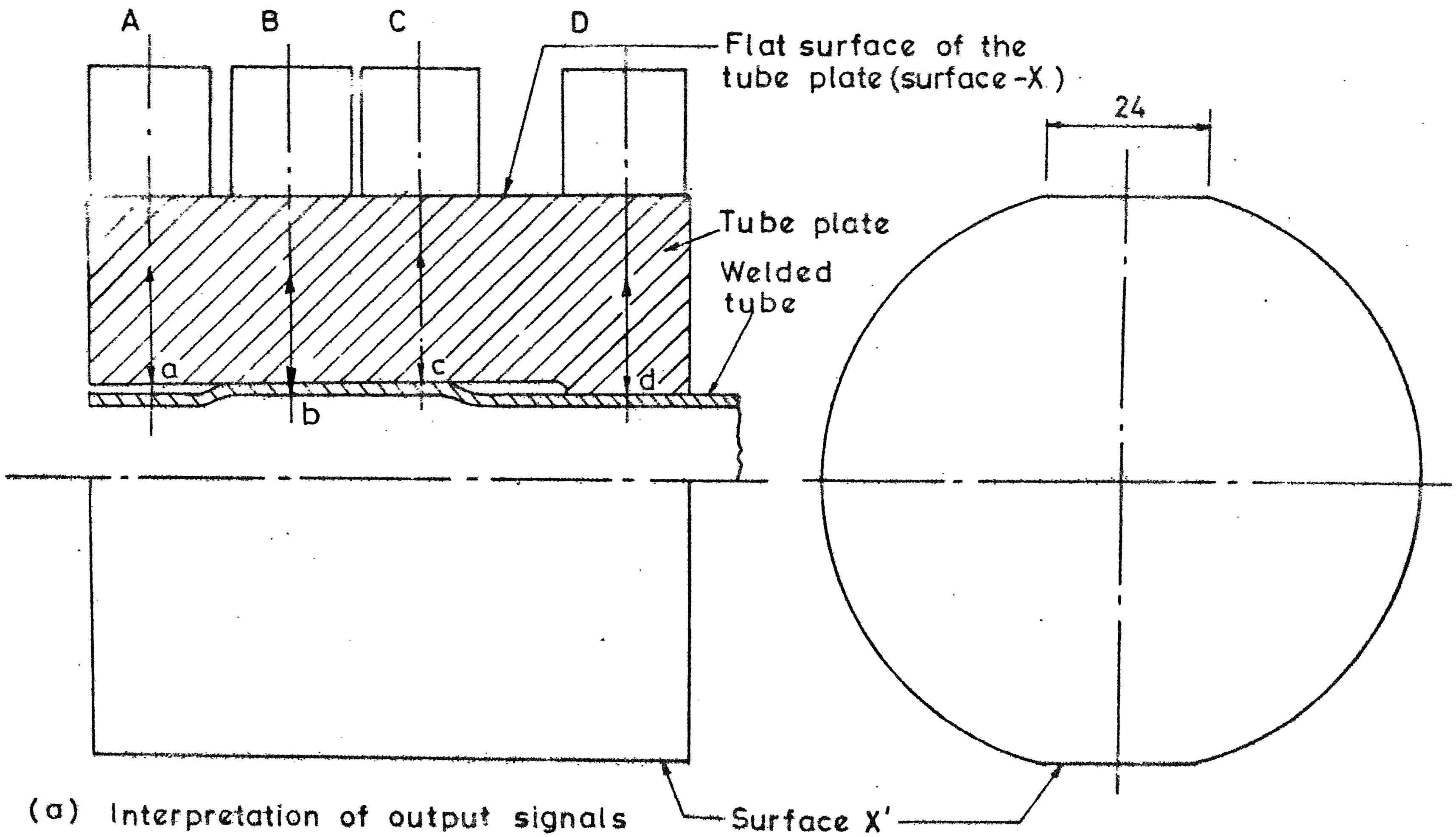


FIG. 22 CALIBRATION OF ULTRASONIC FLAW DETECTOR



(a) Interpretation of output signals

(b) Prepared surface of test piece

FIG. 23 ARRANGEMENT FOR ULTRASONIC TESTING

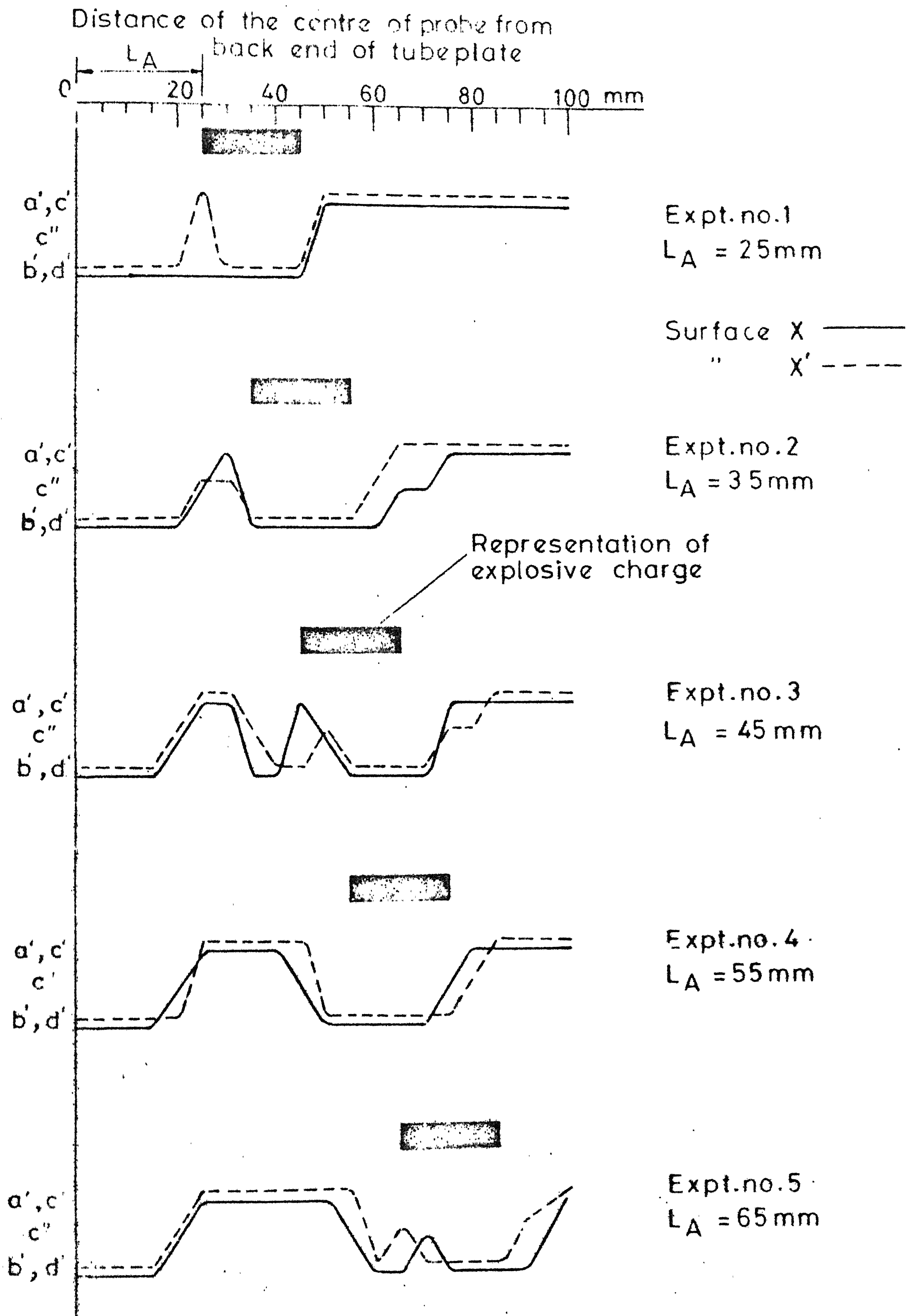


FIG. 24 RESULTS OF ULTRASONIC TESTING. SET-A

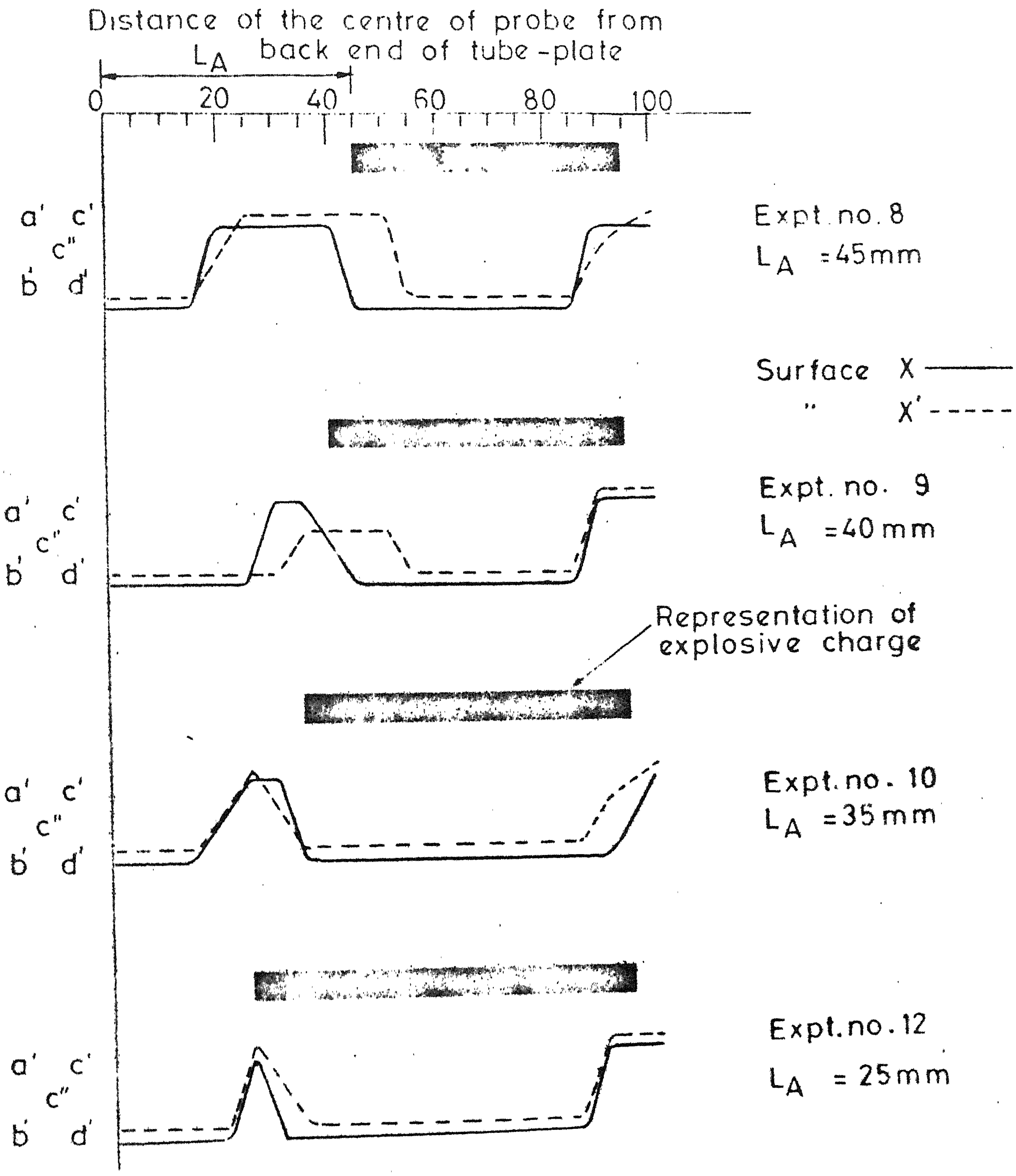


FIG. 25 RESULTS OF ULTRASONIC TESTING : SET - B (2)

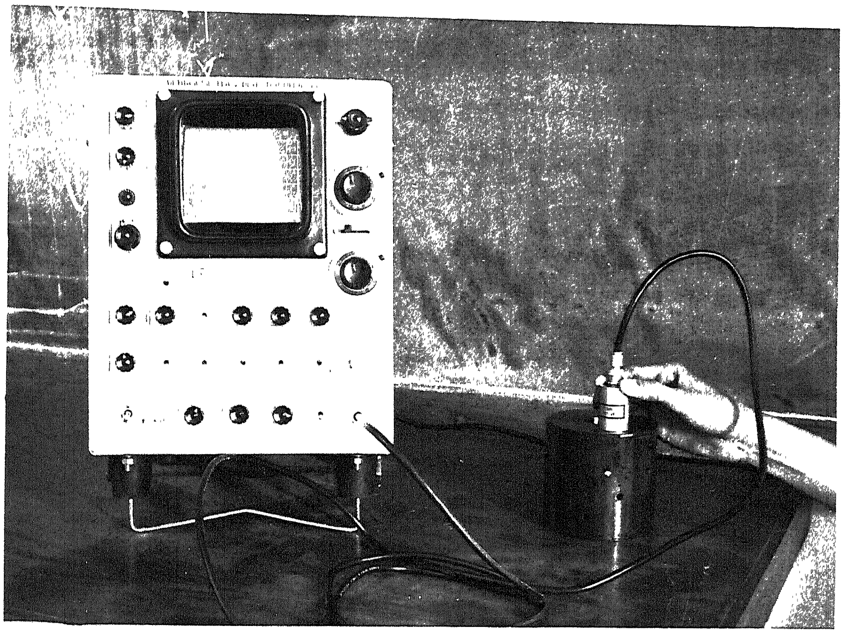


FIG. 26 CALIBRATION OF INSTRUMENT

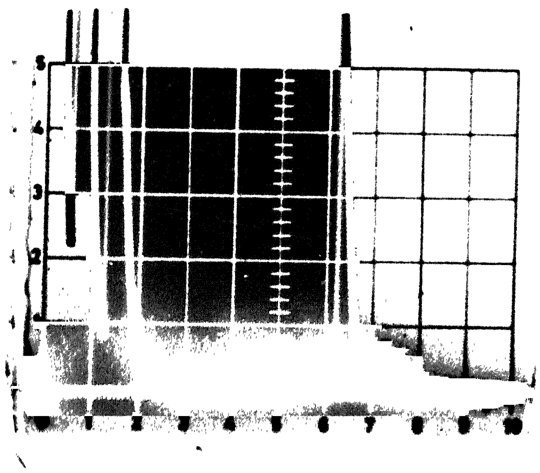
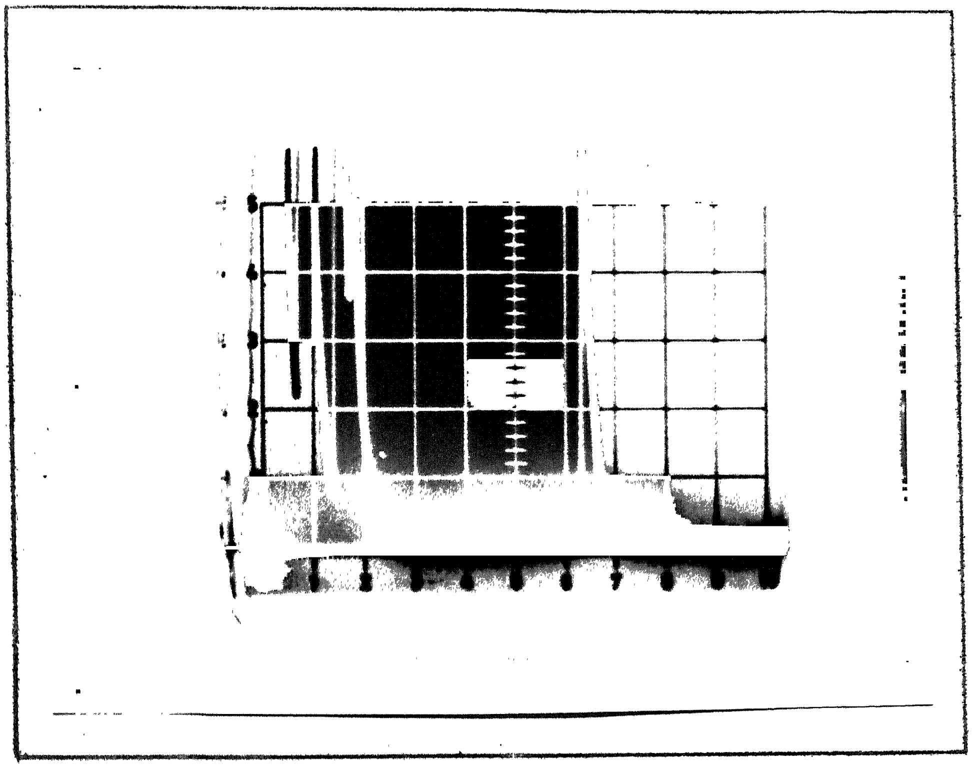
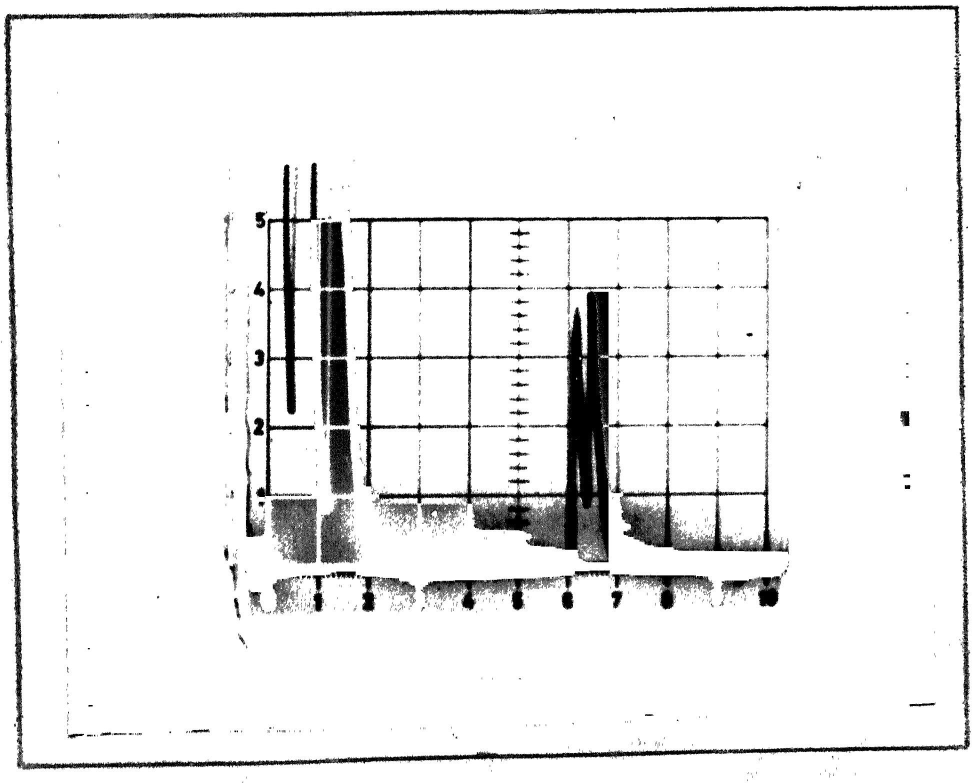


FIG. 27 SIGNALS FROM NO BOND REGION

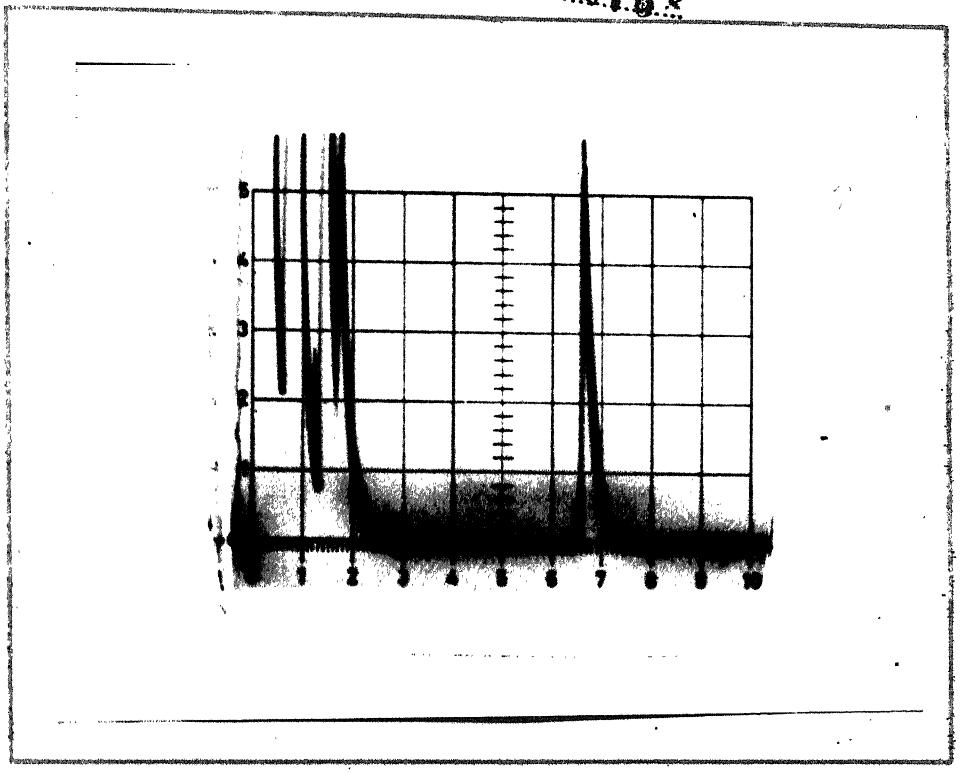


(a) Perfectly welded surface

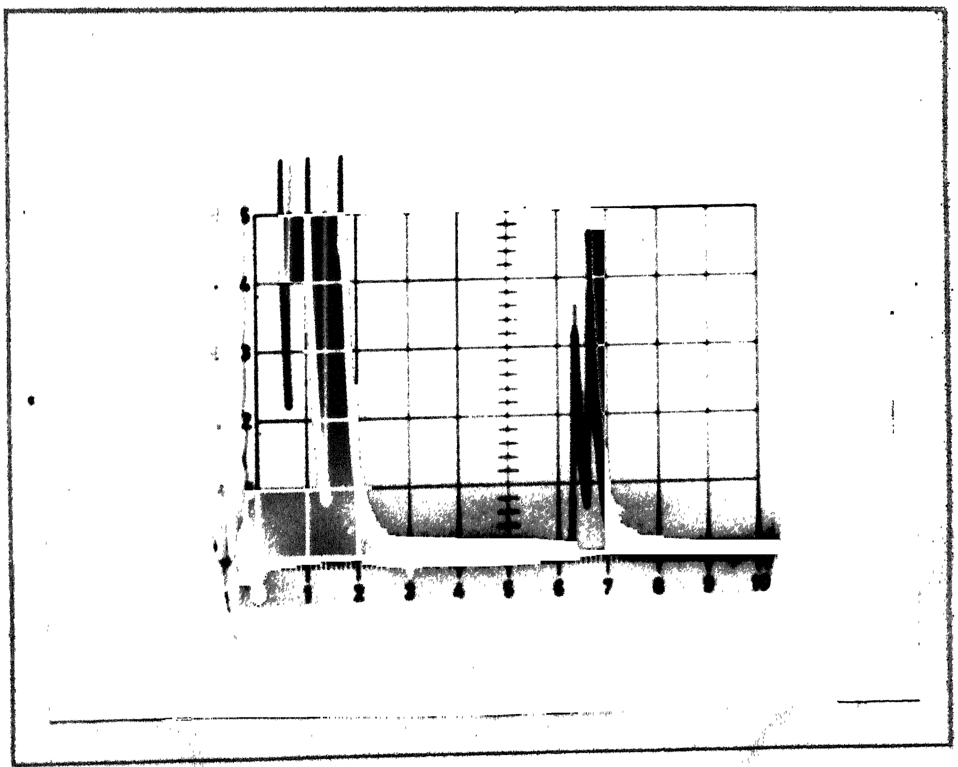


(b) Welded surface with a flaw

FIG. 28 TWO SIGNALS FROM A TEST PIECE ON CRT SCALE



(a) Perfectly welded surface



(b) Welded surface with a flaw

FIG. 29 TWO SIGNALS FROM A TEST PIECE ON CRT SCALE

CHAPTER 3

DISCUSSION OF RESULTS

Explosive welding of tube to tube-plate is studied experimentally as regards tube bulging, and distortion of adjoining holes (or ligament distortion). The results are discussed in the following way :

3.1 BULGING OF TUBE

Experiments on variable charge position tests (Table-1) show that no bulge occurs when the distance of the back face of the charge from the back end of the tube-plate L_A, $L_A \geq 45$ mm. For $L_A = 35$ mm the maximum radial strain occurs at a distance of 5 mm from the back end of the tube-plate. The tube does not show any sign of failure. With $L_A = 25$ mm, the radial strain is very high(37.6×10^{-3}) and the tube shows a longitudinal crack. The results of ultrasonic test (Fig. 24) show that a length approximately equal to the length of the explosive charge gets welded (except a minor flaw in Expt. No. 3) : the weld position is changing with the position of the charge, even though there is a slight bulge for $L_A = 35$ mm (Expt. No. 2), however the weld seems to be perfect.

The effect of increasing charge weight for $L_A = 25$ mm and 45 mm is recorded in Table-2. For $L_A = 25$ mm the tube-plate cracks (Fig. 11). The tube sheared off at the back end for both the cases even though for $L_A = 45$ mm for Expt. No. 7. By comparing

the results of Expt. No.7 and Expt. No.3, it is seen that by increasing the charge weight from 9.25 to 23.10 gms to achieve welding on the whole length of the tube-plate the tube at the back end shears off. It is concluded that exccessive charge weight which may otherwise produce tube velocity V_t within limit (Section 1.5.1) may cause damage to the tube and tube-plate.

The results of experiments using hollow charge varying from 12.3 to 17.3 gms are shown in Table-3. Distance L_A is varied from 45 to 25 mm. Results of ultrasonic test show that the length of the welded portion corresponds with the length of the charge (Fig. 25). Welding on the whole length of the tube-plate is achieved for $L_A = 25$ mm. when the corresponding length of the tube is filled with charge. However tube at the back end shows an excessive bulge with radial strain (45.3×10^{-3}). Radial strain is equally high (Fig. 14) for $L_A = 30$ mm corresponding to weight of charge of 16 gms, and the test piece showed a thin longitudinal crack (Fig. 17). For $L_A = 35$ mm no bulge is observed and a fair length of the test piece gets welded (Fig. 25) without any flaw (Expt. No. 10).

It is evident from the results that the charge weight and shape play a very important role in obtaining successful welding. For the present case a hollow charge of 14.8 gms corresponding to $L_A/D = 1.25$ gives optimum results as regards bulging and welding over a length of the tube.

3.2 LIGAMENT DISTORTION

Figure 20 shows the variation of radial deformation ligament thickness for mild steel tube-plate for two tube materials (1) copper (curve-B), and (2) stainless steel (curve-D). Theoretical curves from equation (4) (Section 1.5.3) using following general properties of the materials are also plotted in the Fig. 20.

TABLE-4 PROPERTIES OF MATERIALS USED

Material / Properties	Mild Steel (Tube-plate)	Copper (Tube)	Stainless steel (Tube)
Hardness (VHN)	164	-	-
Density (gm/cm^3)	-	8.9	7.8
K/σ	1.54×10^{-11} (for VHN=145)	-	-

Since the hardness of the mild steel tube-plate is somewhat greater than the hardness of the tube-plate used for finding (K/σ) [21] used in the equation 4 (Table-4), therefore experimental values of radial deformation of adjoining holes are lower than theoretical values for all ligament thicknesses, however there is a need to establish K as a universal constant. Values of representative stress σ should be found for each tube-plate material.

CHAPTER 4

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

4.1 CONCLUSIONS

Following conclusions are drawn on the basis of experimental results presented in this work :

(1) For welding of copper tube of diameter 28.7 mm and thickness 1.75 mm to mild steel tube-plate, a hollow charge of 14.8 gms spread over a length of 60 mm from the front end, and leaving L_A = 35 mm at the back end is optimum from the point of view of minimum bulge of the tube.

(2) Ultrasonic testing technique provides a satisfactory method for testing the soundness of the weld. However for commercial applications there is a need to develop a suitable probe which will scan from the inside of the tube.

(3) The theoretical analysis proposed by Williams [21] provides a reasonable estimate of ligament distortion for the purpose of designing.

(4) A welded piece (Expt. No.3) is cut into two halves as shown in Fig. 30. Weld surface is cleaned and examined. It appears that upto a distance of 30 mm from the front end of the tube-plate no bonding occurs, after that for a length of 35 mm weld seems to appear. However there is a need to establish die-penetrant test for exact location of flaw within the welded zone of the specimen.

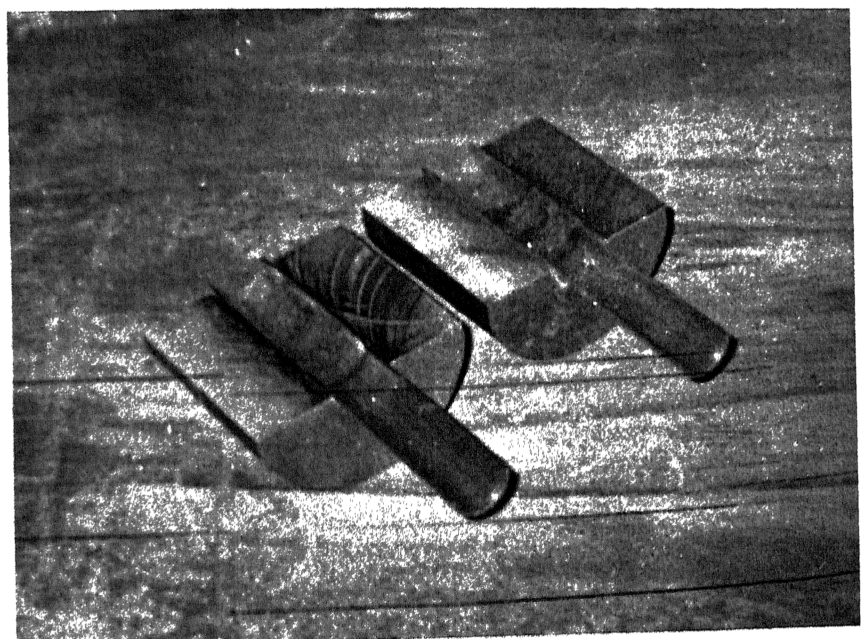


FIG. 30 A WELDED PIECE (Expt.no.3) SHOWN IN TWO HALVES

4.2 SUGGESTIONS FOR FURTHER WORK

(1) There is a need to study the effect of charge weight on the deformation on the bulging of tube and deformation of tube-plate in order to estimate the limiting charge.

(2) There is a need to develop a suitable probe for ultrasonic testing for scanning inside of the tube.

APPENDIX-A

SAMPLE CALCULATION FOR CHARGE WEIGHT

Tube impact velocity is given by Gurney's equation [23]

$$V_t = \sqrt{2E_E} \times \sqrt{\frac{2R}{2+R}} \times n \qquad (5)$$

For calculating E_E following procedure is adopted.

For nitroglycerin –

Energy (Q_H) released during explosion (in terms of heat units)

$$Q_H = 1486 \times 10^3 \quad \text{cal/kg.}$$

Using First law of Thermodynamics, E_E can be written as :

$$E_E = JQ_H$$

$$= 4.17 \times 1486 \times 10^3 \quad \text{joules/kg}$$

$$= 4.17 \times 1486 \times 10^3 \quad \text{kg-m}^2/\text{sec}^2/\text{kg}$$

and

$$\sqrt{2E_E} = \sqrt{2 \times 4.17 \times 1486 \times 10^3}$$

$$= 3520.4 \quad \text{m/sec}$$

R ratio is calculated with ref. to charge pack.

m_S = wt. of explosive/unit length

= $\pi/4 \times (\text{dia of explosive charge})^2 \times$ density of the charge

= $\frac{\pi}{4} \left(\frac{20.5}{10}\right)^2 \times 1.4 = 4.62$ gm/cm.

m_R = wt. of tube/unit length

= π x tube dia. x tube thickness x tube density

$$= \frac{\pi \times 28.7 \times 1.75 \times 8.9}{100} = 14.034 \text{ gm/cm.}$$

m_B = wt. of buffer/unit length

= π x buffer dia. x buffer thickness x buffer density

$$= \frac{\pi \times 24.5 \times 2 \times 1.2916}{100} = 1.988 \text{ gm/cm.}$$

which gives R ratio as :

$$R = \frac{4.62}{14.043 + 1.988} = 0.288$$

Now taking n = 0.24 and using Gurney's equation (5) :

$$V_t = 423.92 \text{ m/sec.}$$

The effective angle of incidence β is calculated using velocity diagram for parallel arrangement (Fig.

$$\beta = \tan^{-1}\left(\frac{V_t}{V_D}\right) = \tan^{-1}\left(\frac{423.92}{2500}\right) = 9^{\circ}38'$$

For parallel arrangement :

$$V_W = V_D = 2500 \text{ m/sec.} \quad ; \quad V_F = \frac{V_D}{\cos\beta} = \frac{2500}{\cos(9^{\circ}38')}$$

$$= 2535.76 \text{ m/sec.}$$

and sonic velocities in the tube-plate and tube are:

$$V_{STP} = 4600 \text{ m/sec.} \quad ; \quad V_{ST} = 4000 \text{ m/sec.}$$

Therefore

$$\frac{V_W}{V_{STP}} = \frac{2500}{4600} < 1$$

and

$$\frac{V_F}{V_{ST}} = \frac{2535.76}{4000} < 1.$$

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REPORT OF M. TECH. THESIS EXAMINATION

(To be filled in Duplicate)

Name...Roll No.........................

Department..

Date of Registration in Programme...

Thesis/Project Title..

....

Date Submitted...

Date of Oral Examination...

Thesis Supervisor (s)..

Report of the Board :

Thesis : Acceptable/Not Acceptable

Thesis Committee

Examiners	Department	Signatures
....	....	....
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Thesis Supervisor | Convenor, DPGC

Date : | Date :

FOR POST-GRADUATE OFFICE USE ONLY

Total Course Units = CPI =

Total Thesis Units =

Chairman
S. P. G. C.

The student has completed the programme

on...

IITK-PG 21

REPORT OF M. TECH. THESIS EXAMINATION

(To be filled in Duplicate)

Name...Roll No.........................

Department...

Date of Registration in Programme...

Thesis/Project Title..

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Date Submitted...

Date of Oral Examination..

Thesis Supervisor (s)...

Report of the Board :

Thesis : Acceptable/Not Acceptable

Thesis Committee

Examiners	Department	Signatures
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Thesis Supervisor

Convenor, DPGC

Date :

Date :

FOR POST-GRADUATE OFFICE USE ONLY

Total Course Units =

CPI =

Total Thesis Units =

Chairman
S. P. G. C.

The student has completed the programme

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REPORT OF M. TECH. THESIS EXAMINATION

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Thesis Supervisor

Convenor, DPGC

Date :

Date :

FOR POST-GRADUATE OFFICE USE ONLY

Total Course Units =

CPI =

Total Thesis Units =

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S. P. G. C.

The student has completed the programme

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Thesis Supervisor

Convenor, DPGC

Date :

Date :

FOR POST-GRADUATE OFFICE USE ONLY

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